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Risk Assessment Calculations Using MEPAS, an Accepted Screening Methodology, and an Uncertainty Analysis for the Reranking of Waste Area Groupings at Oak Ridge National Laboratory, Oak Ridge, Tennessee

L. Shevenell
F. O. Hoffman
D. MacIntosh

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ORNL Environmental Restoration Program

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Author Affiliations

L. Shevenell, who is employed by the Department of Civil Engineering at The University of Tennessee, Knoxville, is on subcontract to the Environmental Sciences Division, Oak Ridge National Laboratory, Martin Marietta Energy Systems, Inc. D. MacIntosh is employed by Indiana University, Bloomington. F. O. Hoffman is a member of the Environmental Sciences Division.

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EXECUTIVE SUMMARY

In a previous report [Shevenell and Hoffman 1991 (ORNL/ER-47)], flaws in the methodology of the Multimedia Environmental Pollutant Assessment System (MEPAS) methodology are identified, and the specific application of MEPAS to Waste Area Groupings (WAGs) at the Oak Ridge National Laboratory (ORNL) is investigated. These flaws can largely be attributed to the application of the model, rather than to the model code itself, and to the use of Hazard Potential Indices (HPI) rather than health risks to rank the WAGs. As a result of these findings, the current work was undertaken with the purpose of addressing several issues.

The purpose of this work is to (1) identify important contaminants; (2) identify the most important transport pathway; (3) determine more site-specific and consistent parameter values and exposure pathways; (4) use uncertainty analysis and the uncertainty about the calculated health risks to rank the sites; and (5) determine the sensitivity of calculated risks to uncertainty in particular parameters and pathways.

Four radionuclides were selected for ranking of WAGs in this report because these contaminants are believed to be among the most important at all ORNL WAGs. The contaminants selected were ^{60}Co, ^{137}Cs, ^{90}Sr, and ^{3}H. The assessment endpoint was the maximum exposed individual at each of two receptors: on-site at WAG 2 and off-site at Clinch River mile 9.5

MEPAS originally modeled both surface water and groundwater transport pathways, whereas the current work focuses on surface water transport. The emphasis on the surface water transport pathway is based on three considerations. First, it is difficult to ascertain how source concentrations were obtained for the original MEPAS rankings; hence, new source concentrations were required for the current work. Second, because the true concentrations of contaminants buried in each of the WAGs are unknown, modeling of the groundwater pathways (leaching through the WAG and groundwater transport to on-site surface water discharge) was abandoned. Finally, it is believed that the majority of contaminants discharge from runoff and groundwater to on-site surface waters. Hence, measured concentrations and flow rates of on-site surface water were used to calculate risks associated with each WAG.

Because ORNL/ER-47 suggests that bioaccumulation factors and transfer coefficients used by MEPAS may not be reliable for site-specific evaluations, a comparison was made between results of the MEPAS formulation and parameters and those recommended by the National Council on Radiation Protection and the International Atomic Energy Agency for generic screening calculations. The parameter values recommended by the NCRP were adjusted to reflect site-specific climate and behavior patterns when necessary. Human health risks associated with contaminants released from the WAGs are calculated using a method suitable for screening, referred to as the ORNL/ESD method (the method used by the Environmental Sciences Division at ORNL) in this report. Risks associated with surface water contamination are modeled, and the following pathways are considered: vegetable, fish, beef, water, and milk consumption; shoreline exposure; ground exposure from irrigation.

The differences in rankings of WAGs between the MEPAS and ORNL/ESD formulations are partly the result of different parameter values and models used. Because the uncertainty of risk assessment parameters results in large differences in calculated risks and ranking of WAGs, the overall effects of parameter uncertainty were considered in an uncertainty analysis. Uncertainty analyses are needed to reliably rank waste sites according to potential risks associated with site contaminants. Uncertainty analysis indicates that the greatest potential risk to human health via surface water exposure pathways is posed by WAG 1; WAGs 2, 6, and 7 (WAGs 2, 6, 7 are combined to form one hypothetical WAG); and WAG 4. The results of the study using uncertainties about all model parameters indicate that the WAGS should be considered for further investigation, or remediation, in the following order: (1) WAG 1; (2) WAGs 2, 6, and 7 (combined); and WAG 4; (3) WAGs 3, 5, and 9; (4) and WAG 8. When uncertainty about all model parameters is propagated through the calculations, WAG 1 risks may not be distinguishable from the risks of WAGs 2, 6, 7 (combined) and WAG 4. These risks cannot be distinguished, nor can the risks attributed to WAGs 3, 5, and 9.

Several parameters contributing to the uncertainty in the total risk at each WAG are common among all WAGs. Most notable among these parameters is the risk conversion factor for exposure to radionuclides. Holding these parameters constant to account for only the uncertainty in parameters unique to the risk assessment for a particular WAG would reduce the overall relative uncertainty for each WAG and thus decrease the extent to which the error bounds between WAGs would overlap. When additional calculations are made using only the uncertainty in contaminant concentrations, there is less ambiguity in the rankings. This simplified procedure indicates that the WAGs should be ranked in the following order: (1) WAG 1; (2) WAGs 2, 6, and 7 (combined); and WAG 4; (3) WAG 5; (4) WAG 9; (5) WAG 3; and (6) WAG 8.

The deterministic MEPAS modeling effort ranked the WAGs as follows: WAG 5, WAG 7, WAG 4, WAG 6, WAG 1, WAG 2, WAG 9, and WAG 3. If exposure to currently contaminated sediment and floodplain soil were to be considered, WAG 2 would probably be ranked first. This exposure route, however, was not considered explicitly in the current analysis.

The uncertainty analysis indicates that the dominant contaminant contributing to potential health risks over all pathways is ^{137}Cs with the greatest ^{137}Cs contribution to risk being acquired through fish ingestion. The two pathways contributing most to ^{90}SR attributable risks are the fish and water ingestion pathways.

ABSTRACT

The Waste Area Groupings (WAGs) at the Oak Ridge National Laboratory (ORNL) were reranked with respect to on- and off-site human health risks using two different methods. Risks associated with selected contaminants from each WAG for occupants of WAG 2 or an off-site area were calculated using a modified formulation of the Multimedia Environmental Pollutant Assessment System (MEPAS) and a method suitable for screening, referred to as the ORNL/ESD method (the method developed by the Environmental Sciences Division at ORNL) in this report. Each method resulted in a different ranking of the WAGs.

The rankings from the two methods are compared in this report. All risk assessment calculations, except the original MEPAS calculations, indicated that WAGs 1; 2, 6, 7 (WAGs 2, 6, and 7 as one combined WAG); and 4 pose the greatest potential threat to human health. However, the overall rankings of the WAGs using constant parameter values in the different methods were inconclusive because uncertainty in parameter values can change the calculated risk associated with particular pathways, and hence, the final rankings. Uncertainty analyses using uncertainties about all model parameters were used to reduce biases associated with parameter selection and to more reliably rank waste sites according to potential risks associated with site contaminants. Uncertainty analysis indicates that the WAGs should be considered for further investigation, or remediation, in the following order: (1) WAG 1; (2) WAGs 2,6, and 7 (combined); and 4; (3) WAGs 3, 5, and 9; and (4) WAG 8.

1. INTRODUCTION

1.1 PURPOSE OF WORK

1.1.1 General

Operations and waste disposal activities began at the Oak Ridge National Laboratory (ORNL) in the 1940s, and these activities have introduced a variety of wastes into the environment. In recent years, concern has increased about the potential for adverse health effects and impacts on the environment from contaminant releases from waste sites, and numerous regulations regarding environmental contaminants have been promulgated. The intent of environmental regulations such as the Resource Conservation and Recovery Act (1976) and the Comprehensive Environmental Response, Compensation, and Liability Act (1980) is to minimize potential impacts of contaminants on human health and the environment.

Numerous contaminated areas across the country have been identified. Because finances are limited, it has become necessary to evaluate the contaminated sites and determine which areas pose the most immediate or greatest potential threat to the environment. Potential impacts to human health and the environment can be evaluated through risk assessment calculations. Estimates of risk provide a quantitative means for ranking or prioritizing contaminated areas for investigation and remediation.

1.1.2 ORNL Waste Areas

Several Waste Area Groupings (WAGs) on the Oak Ridge Reservation (ORR) contain and release contaminants to the environment. Although remediation of all the areas may be desirable, it is not practical to achieve this goal for all areas simultaneously. A method must be employed to evaluate the order in which the areas should be considered for site characterization and, perhaps, remediation. The method selected for ranking of waste sites at ORNL is risk assessment. The method discussed in this report involves a screening approach which uses human health risk as an end point (rather than other end points such as regulatory concentration limits). Uncertainty analyses are conducted so that a level of confidence can be placed on the ranking of the waste areas.

1.2 PREVIOUS WORK

An initial ranking of ORNL waste sites was based on the results of the Multimedia Environmental Pollutant System (MEPAS) model (Whelan et al. 1987, Droppo et al. 1989). This model includes transport pathway and exposure pathway modeling and is used to rank potential risks to human health. The rankings are based on a risk related number identified as the Hazard Potential Index (HPI). The ranking effort was directed by DOE's Office of Environmental Audit, and technical support was provided by NUS Corporation, Washington, D.C. An overview of the preliminary environmental surveys of waste sites at ORNL is found in USDOE (1991).

In a previous report (Shevenell and Hoffman 1991), the MEPAS methodology is evaluated and flaws identified. Because some of the practices could result in unrealistic rankings of the ORNL waste sites, additional investigations were warranted. Based on the results of this previous work, the following items were selected for further investigation and changes: transport pathway modeling, bioaccumulation factors and transfer coefficients, contaminant concentrations, maximum individual exposures associated with each Waste Area Grouping (WAG), calculation of risks rather than HPIs, and performance of uncertainty analyses.

It was also reported in Shevenell and Hoffman (1991) that the risks associated with various end points (intruder, maximally exposed off-site individual, average off-site individual, risk to the off-site populations) should be calculated separately. As a result, different exposure scenarios are calculated and used to rank the ORNL waste sites in the current effort.

1.3 APPROACH

1.3.1 Contaminant Concentrations

Four radionuclides were selected for ranking of WAGs because these contaminants are believed to be among the most important at ORNL WAGs. The contaminants selected were ^{60}Co, ^{137}Cs, ^{90}Sr, and ^{3}H. In the original MEPAS rankings, consumption of fish contaminated with polychlorinated biphenyls (PCBs) was the dominant exposure pathway for WAG 2; however, WAG 2 is not the original source of the PCBs. Although WAG 1 is the suspected source of the PCBs, the true source is unknown; consequently, this contaminant is not considered in the current work.

Because it is difficult to ascertain how source concentrations were obtained for previous MEPAS rankings, new source concentrations were developed. Also, because the true concentrations of contaminants buried in each of the WAGs are unknown, modeling of the groundwater pathways (leaching through the WAG and groundwater transport to surface water discharge) was abandoned. Without reliable input concentrations, calculated concentrations in water discharging from the subsurface to surface water will be approximate at best. Also, studies by Moore (1989) indicate that only $\approx$3 cm of the yearly average precipitation of $\approx$132 cm (or $\approx$2 to 3%) recharges the shallow aquifer and that average fluxes in groundwater are relatively small. This suggests that deeper groundwater flow to off-site locations may be negligible in comparison to stormflow and shallow groundwater discharge to surface streams on site. Hence, measured concentrations and flow rates of surface water were used to calculate risks associated with each WAG, because the majority of contaminants are believed to discharge to on-site surface streams.

The concentrations in surface water previously used in MEPAS are not directly comparable to those used in this report. The MEPAS concentrations were calculated based on estimated source inventories, whereas the current values were measured at monitoring stations presumed to be near WAG discharge locations. Many of the source inventories in the previous MEPAS rankings are considered unreliable because of the paucity of data from which these estimates were derived.

Although the groundwater transport pathway is important, yet is not considered explicitly in the current work, its effects on surface water concentrations are implicitly incorporated. Surface water contaminants are derived, in large part, from shallow groundwater flow through waste areas and groundwater discharge to on-site surface streams adjacent to WAGs. This connection between groundwater and surface water on the ORR has been and continues to be studied in the Oak Ridge Reservation Hydrology and Geology Study (ORRHAGS) program (D. K. Solomon, ORNL, personal communication to L. Shevenell, 1991). In the current work, it was deemed inappropriate to make predictive calculations of groundwater contaminant concentrations because substantial uncertainty exists about the amounts and types of contaminants contained in each waste area. Without realistic and reliable contaminant inventories at the WAGs, no realistic predictions of groundwater contaminant concentrations can be made. The original MEPAS formulation attempted predictive modeling based on insufficient information. The current work addresses this issue by using current surface fluid concentrations, largely a function of groundwater transport, which are known to impact the environment. It is assumed that all exposure is through surface water use and contact (i.e., no water wells are assumed to be drilled on the WAG).

The new contaminant flux rates were obtained from concentration and flow rate data from surface water monitoring stations (Borders et al. 1989; Kornegay 1990) (see Fig. 1 for locations). Note that WAG 1 is the main ORNL plant area. J. R. Trabalka (of ORNL, personal communication with L. Shevenell, 1991) made crude estimates of current contaminant fluxes based on the data in these reports using the following scheme:

1. The White Oak Dam (WOD) flux minus the X14 and X13 fluxes was attributed to WAGs 2, 6, and 7. This total was divided by 3 to partition the flux between the three WAGs.

2. The Melton Branch 2 and the High Flux Isotope Reactor/Transuranium Processing Facility pond stations were used to estimate flux at WAG 8.

3. WAG 3 flux was attributed to the Northwest Tributary (NWT) flux.

4. WAG 4 flux was calculated from X14 flux minus GS3 flux.

5. The Melton Branch X13 flux minus the WAG 8 flux was attributed to WAGs 5 and 9. Except for the case of ^{3}H, this flux was divided by 2 to partition the flux between the two WAGs. All ^{3}H is attributed to WAG 5.

6. WAG 1 flux was obtained from the GS3 flux minus the WAG 3 flux.

These concentrations (flux divided by discharge rate) are used to calculate risk associated with surface water. Note that these values may be underestimates of actual release concentrations as a result of some contaminant adsorption (i.e., ^{137}Cs) onto sediments between the release and monitoring locations. Risks associated with surface water contamination are modeled, and the following pathways are considered: vegetable, fish, beef, water, and milk consumption; inadvertent water ingestion; shoreline exposure; swimming; boating; and bathing.

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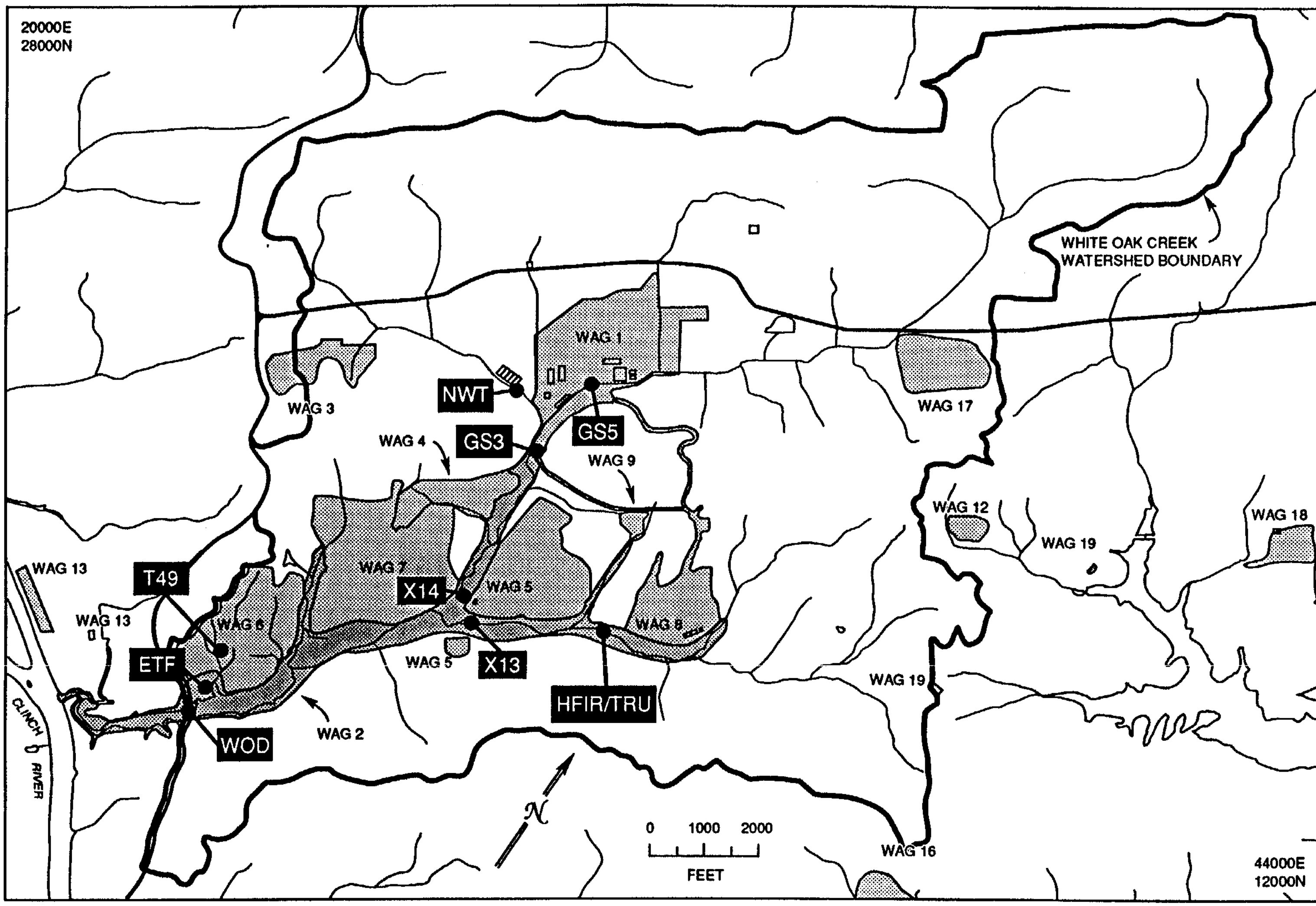

Fig. 1. Locations of the WAGs and the surface water monitoring stations discussed in this report.

1.3.2 Model Parameters

Because Shevenell and Hoffman (1991) found that bioaccumulation factors and transfer coefficients used by MEPAS were not associated with any analysis of reliability for site-specific evaluations at the WAGs, a comparison was made of rankings based on the MEPAS formulation and parameters and those recommended by the National Council on Radiation Protection (NCRP) for screening-level assessments. Generic screening calculations are recommended when site-specific data are not available. The current screening approach, referred to in this report as ORNL/ESD (the method used by the Environmental Sciences Division at ORNL), uses methods recommended by the NCRP and the International Atomic Energy Agency (IAEA) (IAEA 1982). The recommended parameter values were evaluated for applicability to local conditions. As a result, several were adjusted to more accurately reflect local farming and consumption patterns. The ORNL/ESD screening approach uses parameter values and equations that have been derived by national and international committees for use in the absence of site-specific data. This ORNL/ESD method is a screening tool used to determine which contaminants and waste sites may be important and which are clearly unimportant. Neither this method, nor the MEPAS method, can be used to reliably rank waste sites without the use of uncertainty analysis.

1.3.3 Model Formulation

Different philosophies are associated with the ORNL/ESD and MEPAS models. MEPAS calculations assume a 70-year lifetime exposure to contaminants, whereas the ORNL/ESD rankings are based on a 30-year exposure period [based on Environmental Protection Agency (EPA) Risk Assessment Guidance; Directive 9285.6-03]. The 70 years used in the MEPAS formulation is an extreme value. The 30-year value is also conservative given that individuals in the population are unlikely to live in the same locality for an entire 30-year period, with most moving from a location every 9 years (EPA 1991).

Another difference between the ORNL/ESD and MEPAS formulation is that the MEPAS formulation considers the estimated active lifetime of a WAG in the calculations in determining fluxes and concentrations associated with particular WAGs. For instance, a 40-year active lifetime for WAG 2 decreases the concentration associated with the WAG by multiplying the estimated concentration by 40/70 years (40/70 = active lifetime divided by exposure time). In the ORNL/ESD calculations, the release is considered to be continuous and not related to an "active lifetime." For each ranking effort in the current work, two MEPAS-type calculations were made: one using the active lifetime of the system (i.e., with time weighting) and one neglecting the active lifetime of the system (i.e., without time weighting). This was done because the use of active lifetimes of 6.4 to 110.4 years for some WAGs in the original MEPAS work appears to be arbitrary, and this practice results in altering measured fluxes and concentrations for no apparent reason. Also, the fact that a WAG is no longer active does not mean it no longer contributes to surface water contamination resulting from surface runoff and subsurface leaching. For this reason, the practice of using active lifetime is not followed in the ORNL/ESD calculations, and the different methods of calculation are compared (see Sect. 2.1).

Another difference between the original MEPAS formulation and the current ranking scheme is that the ranking of WAGs is now based on calculated risks rather than the HPI [see discussion of HPI in Shevenell and Hoffman (1991)]. In the current analysis, the risks associated with particular contaminants and pathways are tabulated. The risks over all contaminants and all exposure pathways are then summed for each usage location to determine the relative health risk associated with exposure to each WAG's contaminants at the usage location. The WAGs are ranked in descending order with respect to total risk. Additional differences between the two methods (i.e., transfer and usage factors) are outlined in Sect. 2.2.

1.3.4 Uncertainty Analysis

The calculated risk depends on the model parameter values selected; hence, an analysis was conducted to determine the uncertainty associated with these calculated risks based on uncertainty in model parameters. Large uncertainties are associated with many model parameters, such as transfer factors, dose conversion factors, consumption rates, exposure durations, etc. Any rankings obtained without an uncertainty analysis are unreliable because of large inconsistencies in the amount of conservatism used to quantify model parameters for specific contaminant and exposure pathways. In the current work, the uncertainty about the model parameters is propagated through the risk assessment calculations to determine if the risks associated with the particular waste areas can be distinguished (i.e., if they differ significantly). The ORNL waste sites were then ranked based on risk to human health. Ranking of the sites is ultimately used as one component of prioritization for the purpose of scheduling site investigation and remediation activities. Currently, EPA Superfund Guidance (EPA 1989) indicates that the maximally exposed individual is to be targeted in risk assessment calculations. Consequently, this work predominantly focuses on the maximally exposed individual.

2. MEPAS AND ORNL/ESD RANKINGS

2.1 BACKGROUND

Individual health risks attributable to each WAG have been calculated using the revised MEPAS formulation (with the noted changes to the original formulation, both with and without using active lifetime as a consideration) and ORNL/ESD formulations. It is assumed that all of the equations used in the ORNL/ESD and MEPAS formulations adequately represent the conditions and variables leading to the calculated risks. Both methods utilize similar equations for exposure, and all calculations were made on a spreadsheet. The WAGs have been reranked based on these calculations and are compared with the original MEPAS rankings in Table 1. Although calculated risks are larger for on-site than for off-site usage locations, the ultimate rankings listed in Table 1 do not differ between on-site (WAG 2) and off-site (Clinch River) usage locations because the only difference between the usage locations is the contaminant concentration associated with each WAG. The off-site concentrations are consistently lower than those on-site due to the greater flow rate at the Clinch River receptor which acts to dilute concentrations associated with each WAG by an equal amount.

The rankings were the same for each hypothetical human receptor (over all exposure pathways) because the only difference between receptor locations was the value of contaminant concentration in surface water (over all exposure pathways). Hence, the overall risks associated with human exposure at each receptor location assumed in this analysis differ only by a dilution factor, which is constant among WAGs. For ease of analysis, only two receptor locations are considered in the discussion: WAG 2 (on-site) and Clinch River Mile 9.5 (off-site). The same pathways are modeled at both receptors. It is assumed that the concentrations associated with the WAG 2 receptor [Trabalka calculated fluxes divided by discharge over WOD (J. R. Trabalka, ORNL, personal communication with L. Shevenell, 1991)] are evenly distributed in WAG 2 surface water, with no variability in surface water concentrations with location in WAG 2. The current Clinch River receptor is not the same one considered in the original MEPAS rankings, yet the results are comparable because the two sites should only vary by a dilution factor, if all other variables are equal. However, several differences exist between the original and current rankings including different source concentrations, transport pathways, time weightings, etc., all of which contribute to calculated risks (see Sect. 2.2).

Differences between the rankings exist for several reasons in addition to the ones mentioned thus far. Consumption of deer meat, previously attributed solely to WAG 2 in the original MEPAS calculations, is not considered in the current ranking exercise. The home range of deer on the ORR encompasses an area larger than any single WAG. Thus, it is not reasonable to attribute the risk associated with eating deer meat to only one WAG. Also, a different set of equations is used in MEPAS to calculate ^3H exposure than for exposure to the other contaminants (Whelan et al. 1987, Droppo et al. 1989). The screening formulation used in this report simplifies ^3H exposure by assuming one-third of the water in a human body is derived from surface water at the location of interest, which is WAG 2 for on-site exposure or Clinch River Mile 9.5 for off-site exposure (IAEA 1982). In addition, potential human exposure to the current contaminated floodplain and lake sediments of WAG 2 is not taken into consideration.

Table 1. Ranking of ORNL WAGs[a]

Rank No.	Original MEPAS (WAG No.)	MEPAS with time weighting (WAG No.)	MEPAS without time weighting (WAG No.)	ORNL/ESD (WAG No.)
I	5	4	1	1
II	7	1	4	4
III	4	9	5	2[b]
IV	6	3	9	6[b]
V	1	6	3	7[b]
VI	2	5	2[b]	5
VII	9	2	6[b]	9
VIII	3	7	7[b]	8
IX		8	8	3

[a]Rankings are receptor independent. Future tank releases were not considered in the original MEPAS formulation, nor in the ORNL/ESD formulation, for WAGs 1 and 5. Hence, future risks associated with WAGs 1 and 5 may be higher than those calculated in this work.

[b]WAGs 2, 6, and 7 have the same calculated health risks associated with them.

2.2 INTERPRETATION OF RANKINGS

Table 1 lists the overall rankings of the WAGs produced using the two versions of MEPAS and the ORNL/ESD screening formulation. Tables 2 through 7 list the health risks associated with each receptor and calculation method.

The final risks summed over all contaminants and all pathways are not consistently higher or lower with the ORNL/ESD screening approach than those calculated using the MEPAS parameters. Differences in transfer factors (Tables 8 and 9), usage factors (Table 10), and pathway modeling account for variations in ranking among methods. Most usage and consumption rates used in ORNL/ESD are higher than those of MEPAS, suggesting overall risks should be greater in the ORNL/ESD results because of greater exposure to contaminants. Comparing the health risks associated with swimming, boating, and shoreline activities, one finds that ORNL/ESD risks are consistently higher (up to two orders of magnitude) than those of MEPAS. This results in part because larger ORNL/ESD usage factors are specified for a hypothetical, maximally exposed individual. In some cases, these usage factors differ from those assumed in MEPAS by a factor of 150 or more. In addition, the ORNL/ESD accumulation of contaminants in sediments exceeds that calculated using the formulation in MEPAS. Hence, risks associated with these pathways in the ORNL/ESD method are higher than those calculated by MEPAS.

Table 11 lists the order of importance of each pathway in determining health risks. Both versions of the MEPAS formulation, with and without time weighting, indicate the same order of importance, with vegetable consumption being the dominant pathway. The higher risk associated with vegetable consumption may result from the larger irrigation flux used by MEPAS (1200 L m^{-2} $year^{-1}$ compared with a more site-specific value of 240 L m^{-2} $year^{-1}$ employed in the ORNL/ESD formulation). Likewise, the higher contaminant accumulation in sediments causes the shoreline exposure pathway to be dominant in ORNL/ESD calculations.

Although not considered explicitly in this analysis, risks associated with potential exposure to the currently contaminated flood plain and dredged lake sediment could be included in future assessments. Table 12 lists yearly doses presented in Loar et al. (1987) for on-site exposure to contaminated floodplain sediments. Doses associated with WAG 2 (on-site), which currently include surface water exposure but not exposure to floodplain sediments, are included for comparison. Hence, additional risk will be attributed to on-site exposure when currently contaminated floodplain sediments are considered in the formulation. These risks would likely dominate if public access to WAG 2 were to be permitted. The dominant sediment and floodplain contaminant is ^{137}Cs.

Comparing on- and off-site risks (i.e., Tables 2 and 5), one sees that off-site risks associated with all contaminants are lower than those on-site, as expected. However, the overall ranking of the sites remains unchanged, which is the objective of this work. If determination of absolute risks associated with particular receptors were the objective, clearly a higher risk would be attributed to an on-site receptor. The ORNL/ESD screening approach clearly determines that the off-site risk associated with surface water releases from the WAGs is negligible (i.e., all calculated health risks are $<10^{-4}$, which is not distinguishable from a background cancer risk of 10^{-3}). Although off-site risks are low, the remainder of the analysis arbitrarily focuses on off-site risks because selection of receptor location does not alter the ultimate rankings of the WAGs as was discussed in Sect. 2.1.

Table 2. Individual health risk from exposure to radionuclides: Clinch River Mile 9.5 using MEPAS and no time weighting

	^{60}Co	^{137}Cs	^{90}Sr	^{3}H	Total
WAG 1	4.4E-07	1.3E-05	4.0E-05	2.1E-07	5.3E-05
WAG 2	0	1.1E-06	1.6E-06	1.6E-07	2.9E-06
WAG 3	0	8.5E-08	3.0E-06	0	3.0E-06
WAG 4	0	1.1E-06	3.6E-05	1.8E-06	3.9E-05
WAG 5	0	7.9E-08	1.6E-05	6.0E-06	2.2E-05
WAG 6	0	1.1E-06	1.6E-06	1.6E-07	2.9E-06
WAG 7	0	1.1E-06	1.6E-06	1.6E-07	2.9E-06
WAG 8	3.5E-07	0	0	6.2E-08	4.1E-07
WAG 9	0	7.9E-08	1.6E-05	0	1.9E-05
Total	7.9E-07	1.7E-05	1.1E-04	8.5E-06	1.4E-04

Table 3. Individual health risk from exposure to radionuclides: Clinch River Mile 9.5 using MEPAS and time weighting

	^{60}Co	^{137}Cs	^{90}Sr	^{3}H	Total
WAG 1	2.5E-07	7.2E-06	2.3E-05	1.2E-07	3.0E-05
WAG 2	0	6.3E-07	9.1E-07	9.0E-08	1.6E-06
WAG 3	0	8.5E-08	3.0E-06	0	3.0E-06
WAG 4	0	1.1E-06	3.6E-05	1.8E-06	3.9E-05
WAG 5	0	7.2E-09	1.4E-06	5.4E-07	2.0E-06
WAG 6	0	1.1E-06	1.6E-06	1.6E-07	2.9E-06
WAG 7	0	2.4E-07	3.4E-07	3.4E-08	6.1E-07
WAG 8	3.5E-07	0	0	6.2E-08	4.1E-07
WAG 9	0	7.9E-08	1.6E-05	0	1.6E-05
Total	6.0E-07	1.0E-05	8.2E-05	2.8E-06	9.6E-05

Table 4. Individual health risk from exposure to radionuclides: Clinch River Mile 9.5 using ORNL/ESD and no time weighting

	^{60}Co	^{137}Cs	^{90}Sr	^{3}H	Total
WAG 1	2.5E-06	3.9E-05	8.8E-06	4.1E-08	5.0E-05
WAG 2	0	3.4E-06	3.5E-07	3.2E-08	3.7E-06
WAG 3	0	2.6E-07	6.5E-07	0	9.1E-07
WAG 4	0	3.5E-06	7.9E-06	3.6E-07	1.1E-05
WAG 5	0	2.4E-07	3.4E-06	1.2E-06	3.7E-06
WAG 6	0	3.4E-06	3.5E-07	3.2E-08	3.7E-06
WAG 7	0	3.4E-06	3.5E-07	3.2E-08	3.7E-06
WAG 8	2.0E-06	0	0	1.2E-08	2.0E-06
WAG 9	0	2.4E-07	3.4E-06	0	3.7E-06
Total	4.4E-06	5.3E-05	2.5E-05	1.7E-06	8.5E-05

Table 5. Individual health risk from exposure to radionuclides: WAG 2 using MEPAS and no time weighting

	^{60}Co	^{137}Cs	^{90}Sr	^{3}H	Total
WAG 1	9.6E-05	2.7E-03	8.7E-03	4.5E-05	1.2E-02
WAG 2	0	2.4E-04	3.5E-04	3.4E-05	6.2E-04
WAG 3	0	1.8E-05	6.4E-04	0	6.6E-04
WAG 4	0	2.5E-04	7.8E-03	3.9E-04	8.4E-03
WAG 5	0	1.7E-05	3.4E-03	1.3E-03	4.7E-03
WAG 6	0	2.4E-04	3.5E-04	3.4E-05	6.2E-04
WAG 7	0	2.4E-04	3.5E-04	3.4E-05	6.2E-04
WAG 8	7.6E-05	0	0	1.3E-05	8.9E-05
WAG 9	0	1.7E-05	3.4E-03	0	3.4E-03
Total	1.7E-04	3.8E-03	2.5E-02	1.8E-03	3.1E-02

Table 6. Individual health risk from exposure to radionuclides: WAG 2 using MEPAS and time weighting

	^{60}Co	^{137}Cs	^{90}Sr	^{3}H	Total
WAG 1	5.5E-05	1.6E-03	5.0E-03	2.5E-05	6.6E-03
WAG 2	0	1.4E-04	2.0E-04	2.0E-05	3.5E-04
WAG 3	0	1.8E-05	6.4E-04	0	6.6E-04
WAG 4	0	2.5E-04	7.8E-03	3.9E-04	8.4E-03
WAG 5	0	1.6E-06	3.1E-04	1.2E-04	4.3E-04
WAG 6	0	2.4E-04	3.5E-04	3.4E-05	6.2E-04
WAG 7	0	5.1E-05	7.4E-05	7.3E-06	1.3E-04
WAG 8	7.6E-05	0	0	1.3E-05	8.9E-05
WAG 9	0	1.7E-05	3.4E-03	0	3.4E-03
Total	1.3E-04	2.3E-03	1.8E-02	6.3E-04	2.1E-02

Table 7. Individual health risk from exposure to radionuclides: WAG 2 using ORNL/ESD and no time weighting

	^{60}Co	^{137}Cs	^{90}Sr	^{3}H	Total
WAG 1	5.4E-04	8.4E-03	1.9E-03	8.9E-06	1.1E-02
WAG 2	0	7.3E-04	7.7E-05	6.9E-06	8.2E-04
WAG 3	0	5.6E-05	1.4E-04	0	2.0E-04
WAG 4	0	7.7E-04	1.7E-03	7.8E-05	2.6E-03
WAG 5	0	5.3E-05	7.5E-04	2.3E-04	1.0E-03
WAG 6	0	7.3E-04	7.7E-05	6.9E-06	8.2E-04
WAG 7	0	7.3E-04	7.7E-05	6.9E-06	8.2E-04
WAG 8	4.3E-04	0	0	2.7E-06	4.3E-04
WAG 9	0	5.3E-05	7.5E-04	0	8.0E-04
Total	9.6E-04	1.2E-02	5.5E-03	3.7E-04	1.8E-02

Table 8. Comparison of parameters used by MEPAS vs those used in the ORNL/ESD formulation

Parameter	^{60}Co	^{137}Cs	^{90}Sr	^{3}H
Fish BAF[a]				
MEPAS	50	2000	30	1
ORNL	300	2000	60	1
Soil-plant factor				
MEPAS	9.4×10^{-3}	2.0×10^{-3}	2.0×10^{-1}	0
ORNL[b]	8.0×10^{-2}	4.0×10^{-2}	3.0×10^{-1}	0
ORNL[c]	2	0.2	4	0
Veg-milk factor, d/L				
MEPAS	5.0×10^{-4}	5.0×10^{-3}	1.5×10^{-3}	0
ORNL	2.0×10^{-3}	1.0×10^{-2}	2.0×10^{-3}	0
Veg-meat factor, d/kg				
MEPAS	1.0×10^{-3}	3.0×10^{-2}	3.0×10^{-4}	0
ORNL	3.0×10^{-2}	5.0×10^{-2}	1.0×10^{-2}	0
Water purification				
MEPAS	0.2	0.9	0.2	1
ORNL	1	1	1	1
Internal dose conv., Sv/Bq				
MEPAS	7.3×10^{-9}	1.4×10^{-8}	3.8×10^{-8}	1.7×10^{-11}
ORNL	7.3×10^{-9}	1.4×10^{-8}	3.8×10^{-8}	1.7×10^{-11}
Water immersion, Sv/h per Bq/L				
MEPAS	8.9×10^{-10}	1.9×10^{-10}	3.5×10^{-13}	0
ORNL	8.9×10^{-10}	1.9×10^{-10}	3.5×10^{-13}	0
Soil contact, Sv/h per Bq/m^2				
MEPAS	7.03×10^{-12}	1.84×10^{-12}	1.81×10^{-14}	0
ORNL	7.03×10^{-12}	1.84×10^{-12}	1.81×10^{-14}	0

[a]Bioaccumulation factors.
[b]Wet weight for human food crops.
[c]Dry weight for pastures.

Table 9. Comparison of vegetation, dairy, and beef parameters used by MEPAS vs those used in the ORNL/ESD formulation

Parameter	MEPAS	ORNL
Irrigation flux, L m^{-2} $year^{-1}$		
Direct deposition	1200	243.3
Root uptake	1200	243.3
Veg. weathering constant, d^{-1}	0.0495	0.0495
Soil leaching constant, d^{-1}		2.7×10^{-5}
Growing period, d	60	60
Fraction of deposition retained on edible portion of plant	0.25	0.25
Translocation factor (surface to edible)		
Leafy vegetable	1	1
Other vegetable	0.1	1
Crop yield, kg/m^2		
Leafy vegetable	2	2
Nonleafy vegetable	2	2
Pasture		0.12
Soil density, kg/m^2	240	200
Time from harvest to consumption, d		
Leafy vegetable	2	1
Pasture		1
Other vegetable	60	
Fraction of ^3H in plants	0.1	
Fraction of feed contaminated	1	1
Fraction of water contaminated	1	1
Fraction of feed that is leafy	1	
Fraction of feed that is nonleafy	0	
Fraction of feed that is pasture		1
Milk consumption		
Cow feed consumption rate, kg/d	55[a]	16[b]
Cow water consumption rate, L/d	60	60
Time between harvest and consumption, d	4	2
Fraction of ^3H in animal product	0.11	
Fraction of ^3H in feed plant	0.1	
Beef consumption		
Cow feed consumption rate, kg/d	68[a]	12[b]
Cow water consumption rate, L/d	50	50
Time between harvest and consumption, d	20	7
Fraction of ^3H in animal product	0.1	
Fraction of ^3H in feed plant	0.068	

[a]Wet.

[b]Dry.

Table 10. Comparison of usage factors used by MEPAS vs those used in the ORNL/ESD formulation

Usage	MEPAS	ORNL
Exposure duration, years	70	30
Exposure		
Boating, h/year	12	200
Swimming, h/year	12	300
Fishing, h/year	12	12
Shoreline, h/year	12	2000
Ground from irrigation, h/year		2000
Human consumption, kg/year		
Drinking water, L/year	730	800
Fish, kg/year	2.4	11.5
Beef, kg/year	94.9	100
Milk, L/year	109.5	300
Leafy vegetable, kg/year	29.9	18
Nonleafy vegetable, kg/year	189.8	45
Fraction of water[a]		0.33

[a]Fraction of body water originating from contaminated water system. Used in calculation of risk associated with exposure to ^{3}H.

Table 11. Listing of pathways in order of importance in estimating health risks

Rank	ORNL/ESD	MEPAS (time weighting)	MEPAS (no time weighting)
1	Shoreline	Vegetable consumption	Vegetable consumption
2	Fish consumption	Fish consumption	Fish consumption
3	Beef consumption	Drinking water	Drinking water
4	Milk consumption	Beef consumption	Beef consumption
5	Drinking water	Milk consumption	Milk consumption
6	Vegetable consumption	Shoreline exposure	Shoreline exposure
7	Soil irrigation[a]	Water ingestion[b]	Water ingestion[b]
8	Water ingestion[b]	Swimming	Swimming
9	Swimming	Boating	Boating
10	Boating	Bathing	Bathing
11	Bathing		

[a]Soil irrigation refers to the health risk associated with workers in fields irrigated with contaminated water. This pathway is not considered in MEPAS.

[b]Inadvertent water ingestion during bathing.

Table 12. Yearly dose (Sv/year) to humans for exposure to floodplain sediments (Loar et al. 1987) and external exposure pathways calculated with the ORNL/ESD formulation at the WAG 2 on-site receptor

Pathway	Irradiation	^{137}Cs	^{60}Co	^{90}Sr	^{3}H	Total
		Floodplain sediments (Loar et al. 1987)				
Working over sediments	β^a	1.6×10^{-2}	5.6×10^{-4}	2.7×10^{-3}	1.8×10^{-6}	1.93×10^{-2}
	γ^b	3.77×10^{-2}	1.5×10^{-2}			5.27×10^{-2}
Handling fishing gear over sediments	β^a	1.6×10^{-2}	5.6×10^{-4}	2.7×10^{-3}		1.93×10^{-2}
	γ^b	3.77×10^{-3}	1.5×10^{-3}			5.27×10^{-3}
Sun bathing on sediments	β^a	8.0×10^{-3}	2.7×10^{-4}	1.36×10^{-3}	9×10^{-7}	9.63×10^{-3}
	γ^b	1.89×10^{-2}	7.7×10^{-3}			2.66×10^{-2}
		ORNL/ESD external exposure				
Shoreline activity		1.48×10^{-4}	0	7.59×10^{-7}	0	1.48×10^{-4}
Irrigated soil[c]		6.26×10^{-6}	0	3.22×10^{-8}	0	6.29×10^{-6}
		ORNL/ESD external exposure[d]				
Shoreline activity		2.33×10^{-3}	3.73×10^{-4}	5.46×10^{-5}	0	2.76×10^{-3}
Irrigated soil[c]		9.85×10^{-5}	1.68×10^{-5}	2.31×10^{-6}	0	1.18×10^{-4}

[a]Skin dose rate; no distinction made in ORNL/ESD.

[b]Effective whole-body dose rate.

[c]Soil irrigation refers to the health risk associated with workers in fields irrigated with contaminated water. This pathway is not considered in MEPAS.

[d]Exposure at WAG 2 from contributions from all WAGs.

3. PARAMETER UNCERTAINTY

Because substantial uncertainty is associated with most of the parameters used in risk assessment, there is no guarantee of a consistent level of conservatism in calculated risks per contaminants and exposure pathways when constant values of parameters are used. This uncertainty should be incorporated into risk assessment calculations and propagated through the calculations to evaluate if one calculated risk can confidently be ranked higher than another.

3.1 UNCERTAINTY IN CONTAMINANT CONCENTRATIONS

Weekly samples were collected from 1949 to 1980 and were composited proportional to flow in order to evaluate the annual contaminant discharge from all WAGs into the Clinch River (Oakes et al. 1982). These data indicate that contaminant concentrations in surface waters are currently much lower than those measured in the 1950s. In all cases, peaks in contaminant concentrations in surface waters appeared to occur prior to 1980 (i.e., peak ^{137}Cs in 1956 and peak ^{90}Sr in 1958). Because dramatic, and nearly constant, decreases in total contaminant concentrations at WOD occurred between 1949 and 1980, this data set does not accurately represent the expected variability in contaminant concentrations in current discharges because the decreases with time appear to be considerably smaller now than those in the past. Also, this data set does not reflect differences in the hydrologic conditions at each WAG. For instance, discharge contaminant concentrations may have been increasing at one WAG while simultaneously decreasing at another WAG. Additional data must be examined to better evaluate the transient contaminant concentrations.

Direct measurements of contaminant fluxes and concentrations from individual WAGs are not available over long periods of time (years). However, periodic measurements of contaminant concentration at WOD and other ORR monitoring stations are available in the SAS* database from 1987 to 1990. Between 12 and 54 individual samples were collected per year at these stations and their values averaged. Consistent increases or decreases in contaminant concentrations cannot be confidently assigned based on this data, in part because some samples may have been collected during stormflow, while others were not. No consistent sampling of the surface waters occurred that could provide reliable annual discharge data, yet the data can be used to obtain a rough estimate on variability in surface water concentrations. Between 1987 and 1990, ^{60}Co, ^{137}Cs, ^{90}Sr, and ^{3}H concentrations varied about their means by ± 13 to 21%.

Variabilities of fluxes over short time periods and variations in yearly precipitation and discharge over WOD are also investigated to estimate reasonable values for variations in yearly fluxes and concentrations from each WAG. Current knowledge of these variabilities is used to assist in assigning uncertainty to the modeled concentrations. These variabilities are not directly related to uncertainty, yet an understanding of the uncertainty in contaminant concentration can be surmised by noting the current variabilities suggested by a variety of data sources and estimating future variabilities based on the hydrogeologic conditions on the ORR.

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3.1.1 Measured Contaminant Fluxes

Several previous studies have demonstrated that fluxes of contaminants are dependent on stream discharge (and shallow subsurface recharge), with higher fluxes and lower concentrations being observed during high-flow storm events (Huff et al. 1982, Solomon et al. 1989, Wickliff et al. 1989). Contaminants are mobilized during storm events, causing increased total fluxes and decreased contaminant concentrations as a result of dilution during storm flow periods. Data collected in studies of storm flow discharge included measurements of ^{3}H, ^{90}Sr, ^{60}Co, and ^{137}Cs concentrations versus stream discharge at several monitoring points in the White Oak Creek and Melton Branch area of the ORR. Monitoring of stream discharge and contaminant concentration generally began just prior to storm events and continued through storm events that lasted a few hours to a few days. The data generally include one or two background measurements [more in the case of ^{90}Sr in Huff et al. (1982)] and several ($\approx$20 to 40) measurements during the storm. These data represent short time periods biased toward high discharge and high flux periods.

Several of these data sets were examined in the current study to determine the expected standard deviation in contaminant fluxes over time that can be associated with contaminant release from particular WAGs during storms. The calculations indicate that variability about the mean can be quite large as fluxes (and concentrations and flow rates) change rapidly during storm events. The standard deviation about the mean for ^{60}Co is about $\pm$170%, whereas those for ^{3}H, ^{90}Sr, ^{137}Cs fell in the range of $\pm$50 to 80% of the mean value measured during storms. Because these reported data are biased toward high flux, high variability, and short time periods (storm events), these standard deviations are expected to be unrealistically large for periods on the order of years when low flux occurs a higher percentage of the time (between storms). Hence, additional calculations are made to determine more realistic variability of contaminant fluxes over periods of years and to compare these values with the periodic contaminant concentrations reported in the SAS data base.

3.1.2 Precipitation and Surface Water Flow

Records of precipitation and discharge over WOD are used to assist in estimating the variability of these parameters over periods of years. Because precipitation, streamflow, recharge, and base flow are interrelated, the variability of one process should, in general, reflect the variability in the other processes. For instance, in years of low precipitation, flow over WOD decreases, and hence, contaminant flux can be expected to decrease (and concentrations increase) based on the observations made by Wickliff et al. (1989) and Solomon et al. (1989). These data sets, as well as those reported in Huff et al. (1982), indicate that an inverse exponential relationship exists between contaminant concentrations and discharge rates at surface water monitoring stations.

Discharge values for WOD are available in the SAS data base since 1985, whereas precipitation data from nearby stations (Fig. 1) are available since 1952, in some cases. The precipitation records for the following stations are evaluated: Atmospheric Turbulence and Diffusion Division (39 years), ETF (10 years), GS5 (13 years), and T49 (5 years). All four stations contain data for both wet and dry years, thus providing information on expected annual variability in precipitation (and runoff and recharge). Calculations of the mean and standard deviation of precipitation at these stations show that precipitation varies about its mean by ±18 to 27% over periods of 5 to 39 years. As expected, this suggests the possibility of a much smaller long-term variability than is calculated based on measured concentrations during storm events.

The 6-year record of discharge over WOD represents wet, dry, and average years with respect to precipitation. As expected, yearly discharge increases in wet years and decreases in dry years. The variability of discharge over WOD about the mean value calculated from 1985 to 1990 is about ±30% (mean = 21331 L/min; standard deviation = ±6577 L/min). This value is also much less than that calculated using only storm flow flux data and is similar to that obtained with SAS concentration and discharge data. Although a conservative estimate of variability in contaminant fluxes over time is desired, the data from storm flow and long-term annual variations (Oakes et al. 1982) indicate excessive and unrealistic variability when considering future annual variability. Hence, a variability of ±30% about the mean in annual discharge rates at each receptor is assumed realistic.

3.1.3 Uncertainty

Several factors, dominated by unknowns in the hydrologic conditions associated with each WAG, may contribute to uncertainty in contaminant concentrations with time. It is unknown if current or future releases will originate from the original waste area (e.g., trenches) or from a secondary source, in which case concentrations may increase or decrease. Much of the advective transport of contaminants in groundwater occurs through fractures on the ORR, yet contaminants may have also diffused into the poorly permeable matrix portions of the aquifer over time. The matrix intervals could now behave as secondary sources if the concentrations in waste sites and fractures have decreased sufficiently. Evidence for matrix diffusion, and hence secondary sources, is currently being acquired (D. K. Solomon, ORNL, personal communication with L. Shevenell, 1991). For instance, preliminary studies at WAG 5 (Wickliff et al. 1991) suggest that diffusion, rather than advection, dominates contaminant transport in the shallow (0–3 m) subsurface. These researchers also postulate that ^{3}H release from WAG 5 to on-site surface streams may continue to increase until the ^{3}H source is depleted. Hence, it is currently uncertain if contaminant releases from individual WAGs will increase or decrease in the future.

In the opinion of the authors, matrix diffusion is an important process in controlling contaminant mobility in the current conditions at the WAGs. Decades have elapsed since waste disposal was initiated, allowing sufficient time for contaminants to diffuse into the porous matrix intervals. The extent to which matrix diffusion is currently, or will be, dominant at individual WAGs is unknown, and primary sources may remain important at particular WAGs for some time to come. However, it is believed that, in general, release of contaminants from the aquifer matrix by diffusion into fractures will begin to dominate contaminant transport as time proceeds. The process will have several effects on contaminant concentrations discharging to surface waters. First, concentrations will tend to be lower than those measured in previous years when primary sources were clearly dominant. Second, because contaminant transport will be dominated by diffusion, contaminants will be released over longer periods of time (longer than with pure fracture flow) at the reduced concentrations. Third, a more uniform release is expected, with less variability in the maximum and minimum yearly concentrations being observed because the process of rapid flushing of high concentration sources and transport through fractures will become less important (Hillel 1980, p. 277). The variability in contaminant concentrations with time is, therefore, expected to decrease in the next 30 years.

As a result of these effects, which are expected to dominate in the coming years, the uncertainty associated with assigning long-term contaminant concentrations discharging to surface waters is relatively low. The values suggested by the annual variabilities in the previous section are expected to bracket the long-term (30-year) uncertainty in contaminant concentrations. Long-term contaminant releases from the WAGs are expected to lie within the range of the current mean value for each contaminant, $\pm 30\%$. Hence, it is believed that the true, yet unknown, values of concentration will lie within the specified range of uncertainty for a period of ≈ 30 years. As additional hydrogeologic studies are completed, uncertainty in long-term contaminant concentrations in surface waters may decrease.

The uncertainty analysis portion of this work calculates risks based on the expected long-term distribution in discharge rates ($\pm 30\%$), which are translated into uncertainty in concentrations at receptors (Table 13).

3.2 UNCERTAINTY IN RISK ASSESSMENT PARAMETERS

Uncertainty in the parameters used to estimate exposure and risk are based on professional judgment and previously published uncertainty analyses in Hoffman et al. (1982). Hoffman et al. (1982) investigated the uncertainty in model parameters associated with aquatic and terrestrial food chain transport models. Because ^{60}Co produced much lower health risks than either ^{137}Cs or ^{90}Sr (see Sect. 2, Tables 4 and 7 from the ORNL/ESD formulation of this report), the distributions of parameters associated with ^{60}Co are not considered in the uncertainty analysis portion of this work and constant values are assumed. In this analysis, the uncertainty associated with a model parameter is represented as a probability distribution. Each distribution represents subjective degrees of belief that a true, but as yet unknown, value will not be exceeded by any given value in the distribution. Table 14 lists distributions used in the uncertainty analyses for each parameter associated with the risk assessment modeling. Note that parameters associated with swimming, boating, and exposure from fishing are not included in the table. These pathways are neglected in the uncertainty analysis because they were found to contribute to the overall risk by only a minor amount (see Sec. 2.2).

Table 13. Distribution in contaminant concentrations. Lognormal distributions of the concentrations are used in the uncertainty analyses.

	Flow rate (L/year)	Contaminant concentrations (Bq/L)		
		^{137}Cs	^{90}Sr	^{3}H
WAG 1				
(^{137}Cs flux = 8.8 × 10^{11} pCi/year; ^{90}Sr flux = 1.0 × 10^{12} pCi/year; ^{3}H flux = 1.0 × 10^{14} pCi/year.)				
WAG 2 receptor				
Ave discharge	7.74×10^{9}	4.2	4.8	4.8×10^{2}
+30% of discharge	1.01×10^{10}	3.2	3.7	3.7×10^{2}
−30% of discharge	5.42×10^{9}	1.6	6.8	6.8×10^{2}
Clinch R9.5 receptor				
Ave discharge	4.28×10^{12}	7.6×10^{-3}	8.6×10^{-3}	8.6×10^{-1}
+30% of discharge	5.56×10^{12}	5.85×10^{-3}	6.65×10^{-3}	6.65×10^{-1}
−30% of discharge	3.0×10^{12}	1.09×10^{-2}	1.23×10^{-2}	1.23
Standard deviation		2.28×10^{-3}	2.58×10^{-3}	2.58×10^{-1}
WAGs 2, 6, and 7				
(^{137}Cs flux = 2.3 × 10^{11} pCi/year; ^{90}Sr flux = 1.2 × 10^{11} pCi/year; ^{3}H flux = 2.3 × 10^{14} pCi/year.)				
WAG 2 receptor				
Ave discharge	7.74×10^{9}	3.7×10^{-1}	1.9×10^{-1}	1.1×10^{3}
+30% of discharge	1.01×10^{10}	2.8×10^{-1}	1.5×10^{-1}	8.4×10^{2}
−30% of discharge	5.42×10^{9}	5.3×10^{-1}	2.7×10^{-1}	1.6×10^{3}
Clinch R9.5 receptor				
Ave discharge	4.28×10^{12}	1.98×10^{-3}	1.05×10^{-3}	1.98
+30% of discharge	5.56×10^{12}	1.53×10^{-1}	7.99×10^{-4}	1.53
−30% of discharge	3.0×10^{12}	2.84×10^{-3}	1.48×10^{-3}	2.84
Standard deviation		5.94×10^{-4}	4.5×10^{-4}	5.94×10^{-1}
WAG 3				
(^{137}Cs flux = 5.9 × 10^{9} pCi/year; ^{90}Sr flux = 7.4 × 10^{10} pCi/year.)				
WAG 2 receptor				
Ave discharge	7.74×10^{9}	2.8×10^{-2}	3.5×10^{-1}	0
+30% of discharge	1.01×10^{10}	2.2×10^{-2}	2.7×10^{-1}	0
−30% of discharge	5.42×10^{9}	4.0×10^{-2}	5.1×10^{-1}	0
Clinch R9.5 receptor				
Ave discharge	4.28×10^{12}	5.1×10^{-5}	6.4×10^{-4}	0
+30% of discharge	5.56×10^{12}	3.9×10^{-5}	4.9×10^{-4}	0
−30% of discharge	3.0×10^{12}	7.27×10^{-5}	9.1×10^{-4}	0
Standard deviation		1.53×10^{-5}	1.92×10^{-4}	-

Table 13 (continued)

	Flow rate (L/year)	Contaminant concentrations (Bq/L)		
		^{137}Cs	^{90}Sr	^{3}H
WAG 4				
(^{137}Cs flux = 8.0 × 10^{10} pCi/year; ^{90}Sr flux = 9.0 × 10^{11} pCi/year; ^{3}H = 8.7 × 10^{14} pCi/year.)				
WAG 2 receptor				
Ave discharge	7.74×10^{9}	3.8×10^{-1}	4.3	4.2×10^{3}
+30% of discharge	1.01×10^{10}	2.9×10^{-1}	3.3	3.2×10^{3}
−30% of discharge	5.42×10^{9}	5.5×10^{-1}	6.1	5.9×10^{3}
Clinch R9.5 receptor				
Ave discharge	4.28×10^{12}	6.9×10^{-4}	7.8×10^{-3}	7.5
+30% of discharge	5.56×10^{12}	5.3×10^{-4}	6.0×10^{-3}	5.8
−30% of discharge	3.0×10^{12}	9.9×10^{-4}	1.1×10^{-2}	10.7
Standard deviation	-	2.07×10^{-4}	2.34×10^{-3}	2.25
WAGs 5 and 9				
(^{137}Cs flux = 1.1 × 10^{10} pCi/year; ^{90}Sr flux = 7.8 × 10^{11} pCi/year/ ^{3}H flux = 2.9 × 10^{15} pCi/year.)				
WAG 2 receptor				
Ave discharge	7.74×10^{9}	2.6×10^{-2}	1.9	1.4×10^{4}
+30% of discharge	1.01×10^{10}	2.0×10^{-2}	1.4	1.1×10^{4}
−30% of discharge	5.42×10^{9}	3.7×10^{-2}	2.7	2.0×10^{4}
Clinch R9.5 receptor				
Ave discharge	4.28×10^{12}	9.6×10^{-5}	6.8×10^{-3}	25
+30% of discharge	5.56×10^{12}	7.3×10^{-5}	5.2×10^{-3}	19.3
−30% of discharge	3.0×10^{12}	1.4×10^{-4}	9.6×10^{-3}	35.8
Standard deviation	-	2.88×10^{-5}	2.04×10^{-3}	7.5

Table 13 (continued)

	Flow rate (L/year)	Contaminant concentrations (Bq/L)		
		^{137}Cs	^{90}Sr	^{3}H
		WAG 8		
(^{3}H flux = 3.0×10^{13} pCi/year)				
WAG 2 receptor				
Ave discharge	7.74×10^{9}	0	0	1.4×10^{2}
+30% discharge	1.01×10^{10}	–	–	1.1×10^{2}
−30% discharge	5.42×10^{9}	–	–	2.0×10^{2}
Clinch R9.5 receptor				
Ave discharge	4.28×10^{12}	0	0	2.6×10^{-1}
+30% discharge	5.56×10^{12}	–	–	2.0×10^{-1}
−30% discharge	3.0×10^{12}	–	–	3.7×10^{-1}
Standard deviation	–	–	–	7.8×10^{-2}

Fluxes are calculated based on the fluxes used in the ORNL/ESD risk calculations (J. R. Trabalka, ORNL, personal communication to L. Shevenell, 1991). Contaminant concentrations are calculated by dividing the contaminant fluxes of ^{137}Cs and ^{90}Sr for each WAG by the discharge rates (L/year) in this table. In this table, WAGs 2, 6, and 7 are combined to form one WAG. If risks from these individual WAGs were desired, the values listed in this table could be divided by 3. Also note that the ^{137}Cs and ^{90}Sr concentrations for WAGs 5 and 9 are combined, and these 2 WAGs are treated as one WAG in the uncertainty analysis. The listed ^{3}H value applies only to WAG 5.

Table 14. Distribution about risk assessment parameters assumed for uncertainty analysis

Human usage	Distribution	Geometric	Min	Mean	Max	Ref
Exposure duration, years	C			30		*a*
Exposure, h/year						
Shoreline	LTR		25	100	2000	*a*
Ground from irrigation, h/year	LTR		100	1000[c]	8000	*a*
Human consumption						
Drinking water, L/yr^{-1}	TR		91.2	438[c]	730	*a*
Fish, kg/year	LTR		4	11	30	*d*
Beef, kg/year	LN	1.65		94		*d*
Milk, L/year	LN	2.23		95		*d*
Leafy vegetable, kg/year	TLN	1.62	0	18	55	*d*
Nonleafy vegetable, kg/year	TLN	2.16	0	45	540	*d*
Vegetation						
Irrigation flux, mm d^{-1}	LN	1.6		0.67		*a*
$_d$Vegetable weathering constant,						
Leafy	LN	1.68	8.7×10^{-3}	5.7×10^{-2}	3.5×10^{-1}	*d*
Nonleafy	LN	1.77		3.4×10^{-2}		*d*
Pasture	TLN	1.54	8.7×10^{-3}	5.7×10^{-2}	3.5×10^{-1}	*d*
Soil leaching constant, d^{-1}						
^{90}Sr	TLN	7.4	1.1×10^{-7}	6.7×10^{-5}	1.2×10^{-2}	*d*
^{137}Cs	TLN	6.7	4×10^{-7}	1.7×10^{-6}	8×10^{-4}	*d*
^{137}Cs flux to sediments, $\ell/m^2/d$	LTR		10	100	400	*a*
Build-up time in sediments, d	U		1.1×10^{3}	6.05×10^{3}	1.1×10^{4}	*a*
Growing period, d						
Leafy	TR		20	75	120	*d*
Nonleafy	TR		60	100	180	*d*
Pasture	TR		15	30	200	*d*
r/Y, m^2/kg						
Leafy	LN	1.82		0.1		*a*
Nonleafy	LN	2.15		6.02×10^{-2}		*a*
Pasture	TLN	1.55	3.01×10^{-1}	1.8	9.97	*a*
Soil density, kg/m^2	LN	1.12		213		*d*
Soil-plant transfer factor						
Leafy						
^{90}Sr	TLN	3.3	7×10^{-3}	0.33	2.4	*d*
^{137}Cs	TLN	4.5	1×10^{-4}	5.5×10^{-3}	8×10^{-2}	*d*
Nonleafy						
^{90}Sr	TLN	4.5	8×10^{-4}	8.5×10^{-2}	3.4	*d*
^{137}Cs	TLN	4.5	1×10^{-5}	5.3×10^{-3}	1×10^{-1}	*d*
Pasture						
^{90}Sr	TLN	3.42	6×10^{-2}	1.4	46	*d*
^{137}Cs	LN	3.82		4.4×10^{-2}		*d*
Dairy/beef						
Fraction of feed contaminated	C			1[b]		*a*
Fraction of water contaminated	C			1[b]		*a*
Dairy cows						
Feed consumption rate, kg/d	TN	2.6	4.0	11.0	25.0	*d*
Water consumption rate, L/d	LN	1.6		60[b]		*a*

Table 14 (continued)

Human usage	Distribution type	Geometric std. dev.	Min	Mean	Max	Ref
Veg-milk factor, d/L						
^{90}Sr	TLN	1.62	2×10^{-4}	1.2×10^{-3}	8×10^{-2}	*d*
^{137}Cs	LN	1.79		6.7×10^{-3}		*d*
Beef cows						
Feed consumption rate, kg/d	TN	2.0	1.6	8.3	18.0	*d*
Water consumption rate, L/d	LN	1.6		50^{b}		*a*
Veg-meat factor, d/kg						
^{90}Sr	TLN	3.3	4×10^{-5}	5.8×10^{-4}	4×10^{-3}	*d*
^{137}Cs	TLN	2.0	3×10^{-3}	2.1×10^{-2}	2×10^{-1}	*d*
Other						
Shorelide width factor	U		5×10^{-2}	1.75×10^{-1}	3.0×10^{-1}	*a*
Fraction of body water made of ^{3}H contaminated water	LU		0.02		0.33	*a*
Internal dose conversion factor (Sv/Bq)						
^{90}Sr	LN	1.32		1.38×10^{-8}		*d*
^{137}Cs	LN	1.32		1.38×10^{-8}		*d*
^{3}H dose rate factor, Sv/year per Bq/L	LN	1.29		2.5×10^{-8}		*a*
External dose conversion factor, Sv d^{-1} Bq^{-1} m^{2}						
Soil contact ^{137}Cs	LN	1.2		$4.61 \times 10^{-11 b}$		*a*
Soil contact ^{90}Sr	LN	1.2		$4.2 \times 10^{-13 b}$		*a*
Risk factor, Sv^{-1}	LN	2.0		7.2×10^{-2}		*a*
Fish BAF						
^{90}Sr	LN	6.0		11		*d*
^{137}Cs	LN	2.36		400		*d*

[a]Professional judgment of the authors.
[b]Mean value assumed equal to value selected in ORNL/ESD formulation.
[c]Mode.
[d]Hoffman et al. 1982.

4. UNCERTAINTY ANALYSIS

In the uncertainty analyses, risk assessment parameters and contaminant concentrations were allowed to vary according to the distributions described in Sects. 3.1 and 3.2. Each distribution was specified in a spreadsheet type of program (@RISK 1988), which uses the Latin Hypercube method to vary parameter values throughout their distributions over 100 iterations. The purpose of conducting the uncertainty analyses was to determine if conclusive rankings of the waste sites could be made, and if so, to determine the rankings of the WAGs.

In the uncertainty analysis portion of this work, selected contaminant concentrations were redistributed among particular WAGs. For instance, during the deterministic calculations, it was assumed that one-third of the WOD flux minus the X14 and X13 fluxes could be attributed to each of the three WAGs, WAGs 2, 6, and 7. Because it is uncertain what the actual contribution of each of these WAGs is to the total measured flux, the WAGs 2, 6, and 7 were grouped to form one hypothetical WAG contributing 3 times their previous individual fluxes. Similarly, the ^{137}Cs and ^{90}Sr fluxes of WAGs 5 and 9 were combined because greater than 50% of the X13 minus the WAG 8 flux may originate from either WAG 5 or 9. Hence the total measured flux of X13 minus WAG 8 is attributed to both WAGs 5 and 9.

Note on Table 14 that the exposure duration is assumed to be constant. In a preliminary uncertainty analysis, the exposure duration was assumed to have a logtriangular distribution with a minimum of 5 years, a maximum of 70 years, and a mean of 9 years (Hoffman et al. 1982). When the exposure duration was allowed to vary in this manner, it accounted for the majority of the uncertainty in calculated risks and uncertainty in ranking of the WAGs. Hence, this parameter was made constant (30 years) in all subsequent uncertainty analysis calculations to allow evaluation of uncertainty in calculated risk resulting from uncertainty in the other model parameters.

Results of the uncertainty analyses were used to investigate the correlation between calculated risks and pathways and contaminants. The uncertainty analysis indicates that the dominant contaminant contributing to potential health risks over all pathways is ^{137}Cs, with the greatest ^{137}Cs contribution to risk acquired through fish ingestion. The two pathways contributing most to ^{90}Sr attributable risks are the fish and water ingestion pathways.

A large portion of the uncertainty of calculated risk at any given WAG can be attributed to variables in the drinking water pathway and uncertainty in the assumed value of the risk factor (cancer potency factor). A lesser amount of the total WAG risk is associated with the milk consumption pathway and shoreline exposure pathway.

The importance of each parameter in the drinking water pathway is investigated to evaluate pathway sensitivity to parameter uncertainty. The analysis indicates that the risk associated with drinking contaminated water is best correlated with the risk factor compared with risk associated with other model parameters.

Other pathways were also investigated, including milk consumption, shoreline exposure, and fish consumption. The risk factor is important in determining the overall risk associated with the shoreline exposure and fish consumption pathways but is less important in the milk consumption pathway, which is a function of a greater number of parameters than are the shoreline and fish consumption pathways. Uncertainty in contaminant concentration in general produces little uncertainty in risks calculated for any pathway, yet the magnitude of concentration associated with each WAG tends to dictate the ultimate rankings (i.e., a WAG with a higher contaminant concentration generally ranks above a WAG associated with lower contaminant concentrations).

5. RANKING OF ORNL WAGS

To rank each WAG for its contribution to total risk associated with the Clinch R9.5 off-site receptor, the total health risk attributed to each WAG was calculated for the 5th, mean, and 95th percentile (Table 15). The range between the 5th and 95th percentile of a WAG with a higher mean value was compared with the range between the 5th and the 95th percentile of the WAG with a lower mean value to distinguish between the overall ranking of the WAGs. Based on the comparisons from Table 15 and Fig. 2, two distinct groups can be identified, and one group, consisting of WAGs 1 through 7 and 9, can be confidently ranked above WAG 8. There is no overlap in the confidence intervals between the two groups, suggesting that the two groups can be confidently distinguished. Figure 3 presents an alternative graphical approach which can be used to determine if the error bounds on the individual WAG risks overlap. Because WAG 8 has a substantially lower risk associated with it, WAG 8 results are not included on the plot.

The results of the uncertainty analysis conducted by allowing all model parameters to vary indicate that WAGs 2, 6, and 7 (combined) and WAG 4 are indistinguishable, as are WAGs 3, 5, and 9, which appear to contribute lower risks than do WAGs 2, 6, and 7 (combined) and WAG 4. WAG 1 may also be ranked slightly above WAGs 2, 6, and 7 (combined) and WAG 4.

Although there is significant overlap in the error bounds among the WAGs, it may be possible to distinguish between them. Most parameters contributing to the uncertainty in the total risk at each WAG are common among all WAGs. Most notable among these parameters is the risk conversion factor for exposure to radionuclides. Holding these parameters constant to account for only the uncertainty in parameters unique to the risk assessment for a particular WAG would reduce the overall relative uncertainty for each WAG and thus decrease the extent to which the error bounds between WAGs would overlap.

The uncertainty in the rankings shown in Fig. 2 can be reduced in the current model because the same pathways and contaminants were modeled at all WAGs. Hence, the uncertainty in calculated risks resulting from these factors should be the same among all WAGs. In the method in which the ranking was conducted, it may be reasonable to rank the WAGs based only on the uncertainty in contaminant concentrations.

In order to elucidate the rankings, additional calculations were made while holding model parameter values constant and allowing only the contaminant concentrations to vary through their distributions. The results of this new simulation are plotted in Fig. 4, where the error bars are located at the value of risk calculated for the 5th and 95th percentiles. WAG 8 is not included on this plot because it is clearly associated with a much lower risk than the other WAGs; hence, the vertical scales of Figs. 2 and 4 differ. These results suggest that the WAGs can be confidently ranked in the following order: (1) WAG 1; (2) WAGs 2, 6, and 7 (combined) and WAG 4; (3) WAG 5; (4) WAG 9; (5) WAG 3; and (6) WAG 8.

If different contaminants were associated with each WAG, the uncertainty in parameter values would be different for different WAGs (i.e., uncertainty in the dose conversion factor for ^{137}Cs is different from that for PCBs). In this situation, the rankings would need to be based on the uncertainty bounds of model parameters rather than only on the uncertainty in contaminant concentrations. Therefore, rankings in this case would be less definitive than they would if all WAGs were associated with the same contaminants and pathways.

It should also be noted that the uncertainty about all model parameter values must be included when the goal is to evaluate the cost effectiveness of remediation at individual WAGs. The larger uncertainty bounds should be used in this situation because the goal is to decrease the risk to a predetermined level, and uncertainty in the value of the risk must be known if the cost for a particular level of decrease in the overall risk is to be determined.

In this report, the contribution of PCBs from WAG 1 was not considered. Reconsideration of this contaminant, however, would not affect the relative ranking of the WAG since WAG 1 would continue to rank highest in importance. For PCBs, the dominant exposure pathway would be fish ingestion.

Table 15. Total WAG health risk for the 5th, mean, and 95th percentile values of calculated risk

WAG	5th percentile	Mean	95th percentile
1	7.05×10^{-7}	3.14×10^{-6}	1.37×10^{-5}
2, 6, 7	1.55×10^{-7}	7.55×10^{-7}	3.28×10^{-6}
3	2.38×10^{-8}	8.73×10^{-8}	2.81×10^{-7}
4	1.39×10^{-7}	5.44×10^{-7}	1.62×10^{-6}
5	5.11×10^{-8}	2.38×10^{-7}	1.02×10^{-6}
8	1.18×10^{-10}	9.54×10^{-10}	6.69×10^{-9}
9	3.45×10^{-8}	1.15×10^{-7}	3.92×10^{-7}

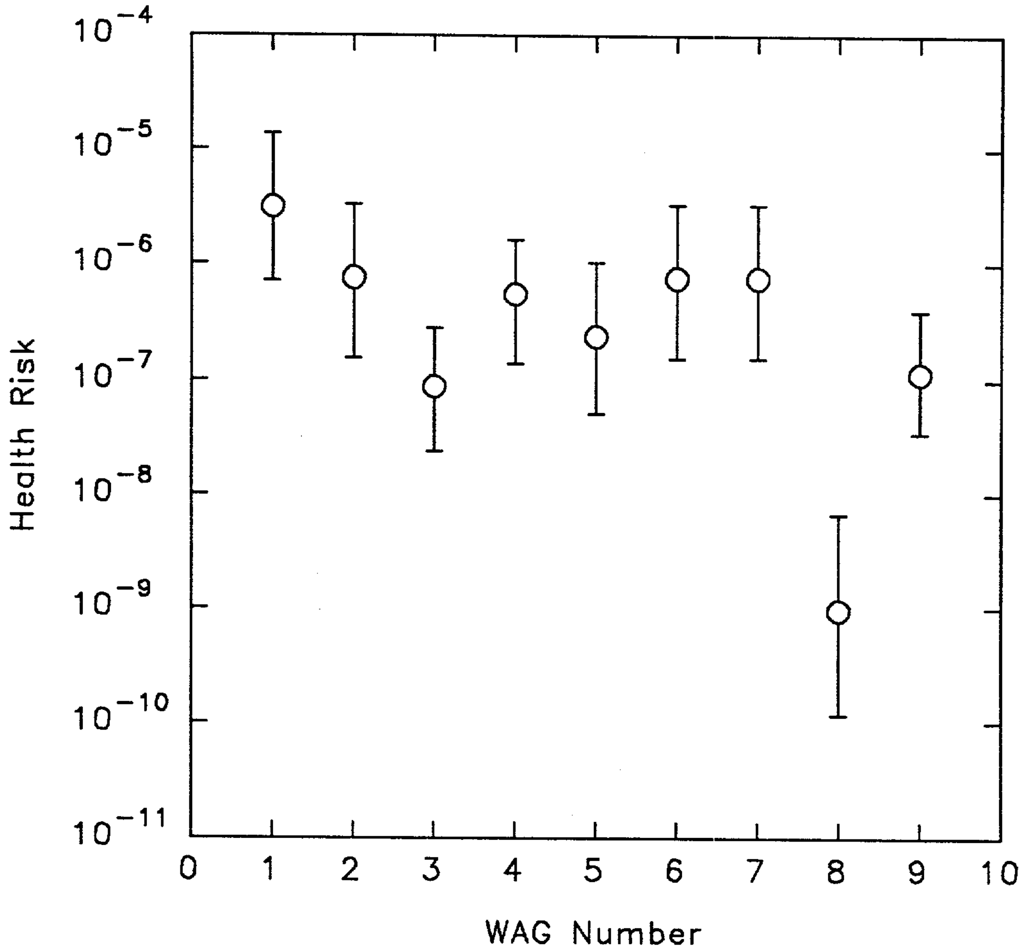

Fig. 2. Plot showing the total health risk attributable to each WAG and the associated uncertainty (error bars) about the calculated risks when all parameter values are allowed to vary. The plotted points are based on the 5th and 95th percentile values listed in Table 15.

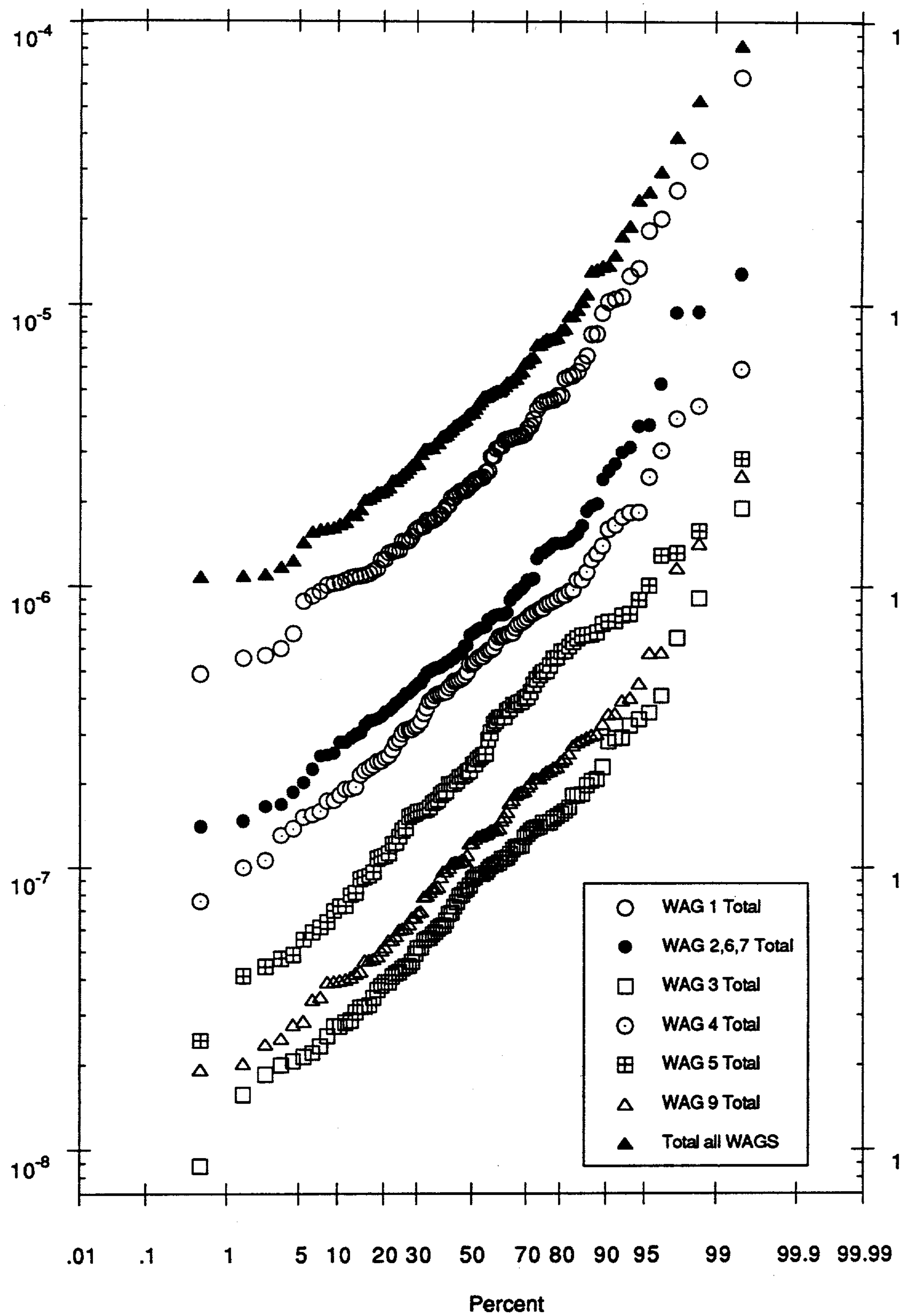

Fig. 3. Plot of individual WAG risks between the 1st and 99th percentile values.

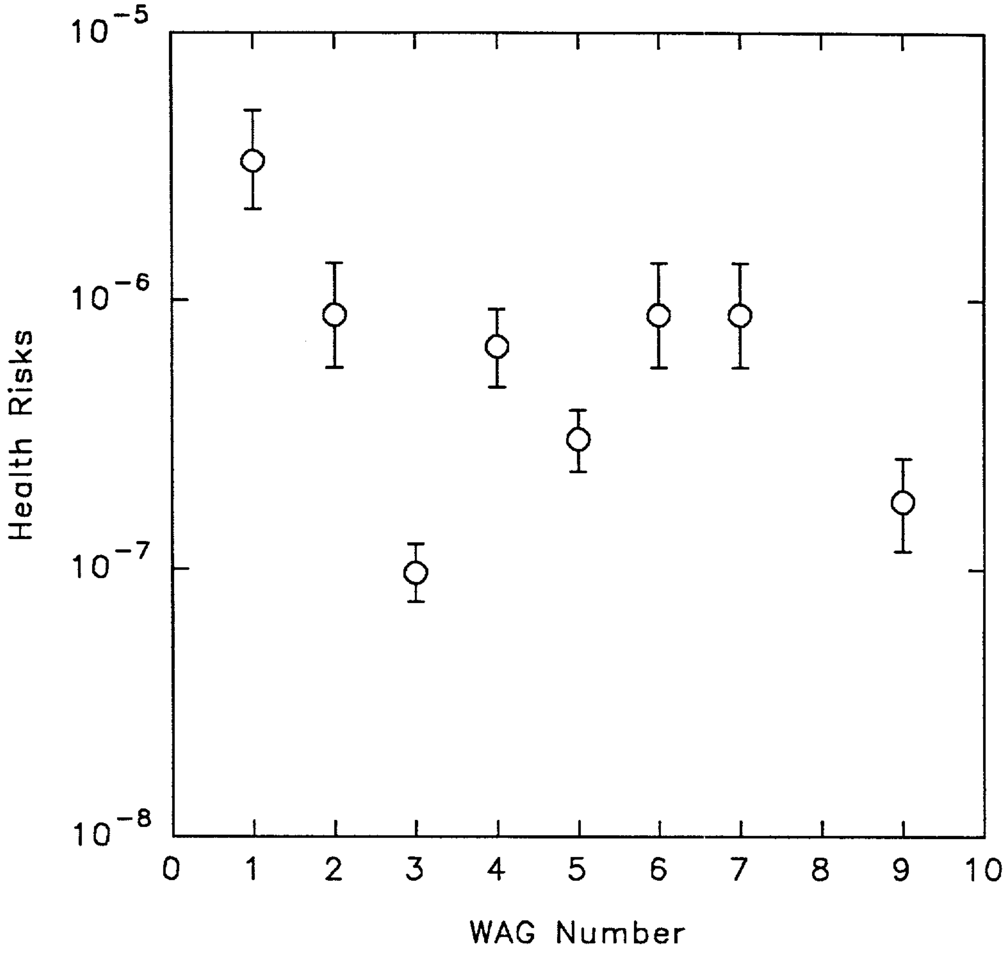

Fig. 4. Plot showing the total health risk attributable to each WAG and the associated uncertainty (error bars) about the calculated risks when only the concentration is allowed to vary. The plotted points are based on the 5th and 95th percentile values calculated in the simulation.

6. RESULTS AND RECOMMENDATIONS

6.1 PRELIMINARY RESULTS

The ranking of WAGs using the different methods (prior to uncertainty analyses) yields disparate rankings. The only agreement among the methods was found for WAGs 1 and 4, which were consistently ranked high. However, it is noted that these calculations are for risks associated with surface water contaminants only. If floodplain and lake sediments were considered in the risk assessment, the risk associated with WAG 2 would be much greater to potential on-site users. Floodplain ^{137}Cs at WAG 2 is likely to pose the dominant risk. Potential off-site transport of these sediments during flood events would also serve to increase the calculated risk. Other sources of potential risk were not considered as a result of assuming surface water contaminants were the only source of risk. For instance, future, as yet unknown, releases caused by leakage from tanks at WAGs 1 and 5 could increase the potential risks associated with these sites. Also, if a homesteader were to reside (build a house, drill a water well, etc.) on WAGs 3 through 7, a greater risk would be attributed to the WAGs because of direct contact of the homesteader with the buried contaminants. Because the current work ranks the WAGs based on concentrations in releases to surface water, this type of scenario is not considered. Additional research and assessments would be required to evaluate risks to potential homesteaders if this scenario is considered realistic.

To obtain maximum individual risks associated with each WAG, on-site surface water concentrations must be considered. Use of this approach and the ORNL/ESD formulation and screening parameters will yield results that indicate which WAGs pose a potential risk to human health and should be investigated further. For instance, Tables 2 through 4 indicate no significant off-site health risks at Clinch River Mile 9.5 and, hence, no need for site (WAG) remediation based on surface water concentrations (i.e., all calculated risks are $<10^{-4}$, which is not distinguishable from a background cancer risk of 10^{-3}). However, Tables 5 through 7 suggest a possible health risk to potential on-site water users and, hence, the possible need for remediation if access to these WAGs by the public is ever permitted or if current institutional controls are lost. However, if population, rather than individual, risks are calculated, off-site risks may be greater than those on-site because several thousand individuals may be exposed off-site whereas the number of hypothetical on-site users is expected to be small.

As seen from the early results of this work, a reliable ranking of the ORNL WAGs will not result from deterministic calculations that assume all parameters are constant. Both absolute and relative values of risk will depend on the models, parameters, and assumptions adopted (i.e., maximum exposure as an intruder enters a WAG when no fences are erected to surround the WAG), all of which are subjectively determined. Hence, ranking of ORNL WAGs is best, and most reliably, accomplished using uncertainty analyses for key radionuclides and exposure pathways.

6.2 UNCERTAINTY ANALYSIS RESULTS

This work demonstrates that deterministic approaches to risk assessments can yield a variety of results depending on the models, pathways, and parameter values selected. Differing amounts of uncertainty are associated with each model parameter. Hence, an uncertainty analysis must be used in conjunction with risk assessment and ranking to determine if distinctions can be made between calculated risks.

The uncertainty analyses discussed in Sect. 4 were used to assist in the ranking of health risks attributed to individual WAGs. Table 16 lists the rankings of the WAGs for the original MEPAS formulation, the revised MEPAS formulation without time weighting, the ORNL/ESD screening model, and the risk assessment model with uncertainty analysis conducted by allowing only concentration to vary. All rankings subsequent to the original MEPAS calculations are substantially different from the original rankings. However, all subsequent calculations consistently indicate that WAG 1 poses the greatest potential risks to human health, especially if institutional controls were to be lost and surface water used to irrigate crops. Inclusion of the potential exposure to currently contaminated floodplain soil and lake sediment due to ^{137}Cs may result in WAG 2 being ranked much higher in importance. The current analysis, however, was restricted to releases to surface water and the potential risks resulting from possible exposure pathways originating from human use of this water. Uncertainty analysis was used to confidently rank the WAGs in the following order: (1) WAG 1; (2) WAGs 2, 6, and 7 and WAG 4; (3) WAG 5; (4) WAG 9; (5) WAG 3; (6) WAG 8. The uncertainty analysis also indicates that the fish consumption pathway is the most important in the calculation of risks at ORNL and that this pathway is most sensitive to uncertainty in the risk factor.

6.3 RECOMMENDATIONS

The evaluation of the original MEPAS rankings and the determination of new rankings based on surface water concentrations and use of an uncertainty analysis lead to recommendations for future work. First, a similar, yet more thorough, procedure should be applied to all waste areas and potential contaminant sources (i.e., WAGs) on the ORR in order to include all potential contaminant sources and rank them appropriately. Current contaminant concentrations should be used in the analysis to identify which sites currently pose a potential threat to human health.

Although the uncertainties in risks calculated for particular pathways are relatively insensitive to the uncertainty in contaminant concentration and generally more sensitive to such parameters as risk factor, the total risks and final rankings associated with different WAGs are highly dependent on contaminant concentration. The same pathways and uncertainties about parameter values were modeled for each WAG, yet they rank differently as a result of varying contaminant concentrations in surface waters to which the WAGs discharge, indicating the importance of acquiring realistic concentration data for each waste area. Also, because it is believed that much of the contaminant discharge from groundwater is to on-site surface streams, rather than by deep groundwater flow to off-site locations, increased efforts in surface water monitoring should be made. Relatively frequent sampling (once or twice per week) of surface waters down-gradient of each waste

Table 16. Ranking of ORNL WAGs

Rank Number	Current rankings[a] at WAGs: Original MEPAS (WAG No.)	MEPAS without time weighting (WAG No.)	ORNL/ESD (WAG No.)	ORNL/ESD—uncert. analysis (WAG No.)
I	5	1	1	1
II	7	4	4	2, 6, 7[c,d]
III	4	5	5	4[d]
IV	6	9	2[b]	5
V	1	3	6[b]	9
VI	2	2[b]	7[b]	3
VII	9	6[b]	9	8
VIII	3	7[b]	3	
IX		8	8	

[a]Rankings are receptor independent.
[b]WAGs 2, 6, and 7 have the same calculated health risks associated with them because the same surface water concentrations are assigned to each of these WAGs.
[c]This represents the combined contribution from WAGs 2, 6, and 7.
[d]WAGs 2, 6, 7 and WAG 4 cannot be confidently distinguished.

site would help in identifying more realistic contaminant concentrations associated with each site, as well as the variability and trend in concentrations with time. This information could help reduce the long-term uncertainty associated with the concentrations used in the current work. Additional monitoring stations should also be established to help differentiate between the risks associated with WAGs 2, 6, and 7, and between WAGs 5 and 9.

7. CONCLUSIONS

Risk assessment results are very user-specific and depend on the user's selection of models, parameter values, and uncertainty about important parameters. Thus the same modeling results cannot be guaranteed when different individuals conduct risk assessments, even when the same, or similar, models are used. In the absence of site-specific data obtained from an appropriate experimental design, subjectivity will always be associated with selection of parameter values and their uncertainties. Because risk assessment modeling represents a highly inexact methodology, uncertainty analyses should always be conducted. Any use of deterministic approaches beyond that of simple screening analysis cannot be considered reliable because the relative differences in uncertainty associated with specific exposure pathways and contaminants are obscured behind the deterministic estimates. This problem is particularly pronounced when model predictions rely on default values applied in the absence of site-specific data.

When different contaminants are associated with individual waste sites, the uncertainty in parameter values differs among the waste sites; the overall rankings would, therefore, need to be based on the uncertainty bounds of model parameters rather than only on the uncertainty in contaminant concentrations. A full uncertainty analysis is also required when the objective of the work is to evaluate the cost effectiveness of remediation of particular waste sites.

Diverging rankings of the ORNL WAGs using deterministic approaches were demonstrated in this work, giving the false impression that one WAG could be confidently ranked above another. Through the use of uncertainty analyses, however, it was possible to rank the ORNL WAGs in a more reliable manner. Risk assessment conducted with uncertainty analyses indicate that ORNL WAGs can be ranked in the following order: (1) WAG 1; (2) WAG 2,6, and 7 (combined) and WAG 4; (3) WAG 5; (4) WAG 9; (5) WAG 3; and (6) WAG 8. Additional surface water concentration data should be collected to help distinguish among the contributions of WAG 2, 6, and 7, and between WAGs 5 and 9.

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APPENDIX

Calculated Yearly Doses (Sv/year) for Each WAG and Exposure Pathway for Both the Clinch River Mile 9.5 Receptor and the WAG 2 Receptor

Table A.1. Calculated yearly doses (Sv/year) for each WAG and exposure pathway for the Clinch River Mile 9.5 receptor

Exposure pathway	^{60}Co	^{137}Cs	^{90}Sr	^{3}H[a]	Total
		All WAGs			
Fish consumption	8.26E-08	8.26E-06	1.65E-06	0	1.0E-05
Milk consumption	2.93E-08	1.81E-06	2.99E-06	0	4.83E-06
Beef consumption	1.19E-07	2.96E-06	4.06E-06	0	7.15E-06
Deer consumption	0	0	0	0	0
Vegetable consumption	7.67E-09	1.15E-07	7.93E-07	0	9.16E-07
Drinking water	1.92E-08	2.87E-07	1.92E-06	0	2.22E-06
Bathing	6.6E-14	1.22E-11	6.85E-12	0	1.91E-11
Swimming	8.78E-10	1.51E-09	6.67E-12	0	2.39E-09
Boating	5.85E-10	1.01E-09	4.45E-12	0	1.6E-09
Shoreline activity	1.72E-06	1.07E-05	2.51E-07	0	1.27E-05
Irrigated soil	7.74E-08	4.54E-07	1.06E-08	0	5.42E-07
Soil ingestion	0	0	0	0	0
Water ingestion	7.18E-10	1.08E-08	7.19E-08	0	8.33E-08
Total	2.06E-06	2.46E-05	1.18E-05	7.89E-07	3.84E-05
		WAG 1			
Fish consumption	4.6E-08	6.02E-06	5.75E-07	0	6.64E-06
Milk consumption	1.63E-08	1.32E-06	1.04E-06	0	2.38E-06
Beef consumption	6.64E-08	2.16E-06	1.41E-06	0	3.64E-06
Vegetable consumption	4.28E-09	8.4E-08	2.76E-07	0	3.64E-07
Drinking water	1.07E-08	2.1E-07	6.67E-07	0	8.87E-07
Bathing	3.68E-14	8.91E-12	2.38E-12	0	1.13E-11
Swimming	4.89E-10	1.1E-09	2.32E-12	0	1.59E-09
Boating	3.26E-10	7.33E-10	1.55E-12	0	1.06E-09
Shoreline activity	9.58E-07	7.81E-06	8.75E-08	0	8.86E-06
Irrigated soil	4.31E-08	3.31E-07	3.7E-09	0	3.78E-07
Soil ingestion	0	0	0	0	0
Water ingestion	4.E-10	7.86E-09	2.5E-08	0	3.33E-08
Total	1.15E-06	1.8E-05	4.09E-06	1.91E-08	2.32E-05
		WAG 2			
Fish consumption	0	5.25E-07	2.3E-08	0	5.48E-07
Milk consumption	0	1.15E-07	4.16E-08	0	1.57E-07
Beef consumption	0	1.88E-07	5.66E-08	0	2.45E-07
Deer consumption	0	0	0	0	0
Vegetable consumption	0	7.32E-09	1.1E-08	0	1.84E-08
Drinking water	0	1.83E-08	2.67E-08	0	4.49E-08
Bathing	0	7.77E-13	9.53E-14	0	8.72E-13
Swimming	0	9.59E-11	9.29E-14	0	9.6E-11
Boating	0	6.39E-11	6.19E-14	0	6.4E-11
Shoreline activity	0	6.81E-07	3.5E-09	0	6.84E-07

Table A.1 (continued)

Exposure pathway	^{60}Co	^{137}Cs	^{90}Sr	$^{3}H^{a}$	Total
Irrigated soil	0	2.88E-08	1.48E-10	0	2.9E-08
Soil ingestion	0	0	0	0	0
Water ingestion	0	6.85E-10	1E-09	0	1.68E-09
Total	0	1.56E-06	1.64E-07	1.46E-08	1.73E-06
		WAG 3			
Fish consumption	0	4.04E-08	4.26E-08	0	8.29E-08
Milk consumption	0	8.86E-09	7.7E-08	0	8.59E-08
Beef consumption	0	1.45E-08	1.05E-07	0	1.19E-07
Vegetable consumption	0	5.63E-10	2.04E-08	0	2.1E-08
Drinking water	0	1.4E-09	4.93E-08	0	5.07E-08
Bathing	0	5.98E-14	1.76E-13	0	2.36E-13
Swimming	0	7.38E-12	1.72E-13	0	7.55E-12
Boating	0	4.92E-12	1.15E-13	0	5.03E-12
Shoreline activity	0	5.24E-08	6.47E-09	0	5.88E-08
Irrigated soil	0	2.22E-09	2.74E-10	0	2.49E-09
Soil ingestion	0	0	0	0	0
Water ingestion	0	5.27E-11	1.85E-09	0	1.9E-09
Total	0	1.2E-07	3.03E-07	0	4.23E-07
		WAG 4			
Fish consumption	0	5.48E-07	5.18E-07	0	1.07E-06
Milk consumption	0	1.2E-07	9.36E-07	0	1.06E-06
Beef consumption	0	1.96E-07	1.27E-06	0	1.47E-06
Vegetable consumption	0	7.63E-09	2.48E-07	0	2.56E-07
Drinking water	0	1.9E-08	6E-07	0	6.19E-07
Bathing	0	8.1E-13	2.14E-12	0	2.95E-12
Swimming	0	1E-10	2.09E-12	0	1.02E-10
Boating	0	6.67E-11	1.39E-12	0	6.81E-11
Shoreline activity	0	7.1E-07	7.87E-08	0	7.89E-07
Irrigated soil	0	3.01E-08	3.33E-09	0	3.34E-08
Soil ingestion	0	0	0	0	0
Water ingestion	0	7.14E-10	2.25E-08	0	2.32E-08
Total	0	1.63E-06	3.68E-06	1.66E-07	5.31E-06
		WAG 5			
Fish consumption	0	3.76E-08	2.24E-07	0	2.62E-07
Milk consumption	0	8.26E-09	4.06E-07	0	4.14E-07
Beef consumption	0	1.35E-08	5.52E-07	0	5.65E-07
Vegetable consumption	0	5.25E-10	1.08E-07	0	1.08E-07
Drinking water	0	1.31E-09	2.6E-07	0	2.61E-07
Bathing	0	5.57E-14	9.29E-13	0	9.85E-13
Swimming	0	6.88E-12	9.05E-13	0	7.78E-12
Boating	0	4.58E-12	6.04E-13	0	5.19E-12
Shoreline activity	0	4.88E-08	3.41E-08	0	8.29E-08
Irrigated soil	0	2.07E-09	1.44E-09	0	3.51E-09

Table A.1 (continued)

Exposure pathway	^{60}Co	^{137}Cs	^{90}Sr	^{3}H[a]	Total
Soil ingestion	0	0	0	0	0
Water ingestion	0	4.91E-11	9.75E-09	0	9.8E-09
Total	0	1.12E-07	1.59E-06	5.54E-07	1.71E-06
		WAG 6			
Fish consumption	0	5.25E-07	2.3E-08	0	5.48E-07
Milk consumption	0	1.15E-07	4.16E-08	0	1.57E-07
Beef consumption	0	1.88E-07	5.66E-08	0	2.45E-07
Vegetable consumption	0	7.32E-09	1.1E-08	0	1.84E-08
Drinking water	0	1.83E-08	2.67E-08	0	4.49E-08
Bathing	0	7.77E-13	9.53E-14	0	8.72E-13
Swimming	0	9.59E-11	9.29E-14	0	9.6E-11
Boating	0	6.39E-11	6.19E-14	0	6.4E-11
Shoreline activity	0	6.81E-07	3.5E-09	0	6.84E-07
Irrigated soil	0	2.88E-08	1.48E-10	0	2.9E-08
Soil ingestion	0	0	0	0	0
Water ingestion	0	6.85E-10	1E-09	0	1.68E-09
Total	0	1.56E-06	1.64E-07	1.46E-08	1.73E-06
		WAG 7			
Fish consumption	0	5.25E-07	2.3E-08	0	5.48E-07
Milk consumption	0	1.15E-07	4.16E-08	0	1.57E-07
Beef consumption	0	1.88E-07	5.66E-08	0	2.45E-07
Vegetable consumption	0	7.32E-09	1.1E-08	0	1.84E-08
Drinking water	0	1.83E-08	2.67E-08	0	4.49E-08
Bathing	0	7.77E-13	9.53E-14	0	8.72E-13
Swimming	0	9.59E-11	9.29E-14	0	9.6E-11
Boating	0	6.39E-11	6.19E-14	0	6.4E-11
Shoreline activity	0	6.81E-07	3.5E-09	0	6.84E-07
Irrigated soil	0	2.88E-08	1.48E-10	0	2.9E-08
Soil ingestion	0	0	0	0	0
Water ingestion	0	6.85E-10	1E-09	0	1.68E-09
Total	0	1.56E-06	1.64E-07	1.46E-08	1.73E-06
		WAG 8			
Fish consumption	3.66E-08	0	0	0	3.66E-08
Milk consumption	1.3E-08	0	0	0	1.3E-08
Beef consumption	5.28E-08	0	0	0	5.28E-08
Vegetable consumption	3.4E-09	0	0	0	3.4E-09
Drinking water	8.48E-09	0	0	0	8.48E-09
Bathing	2.92E-14	0	0	0	2.92E-14
Swimming	3.89E-10	0	0	0	3.89E-10
Boating	2.59E-10	0	0	0	2.59E-10
Shoreline activity	7.62E-07	0	0	0	7.62E-07
Irrigated soil	3.43E-08	0	0	0	3.43E-08
Soil ingestion	0	0	0	0	0

Table A.1 (continued)

Exposure pathway	^{60}Co	^{137}Cs	^{90}Sr	^{3}H[a]	Total
Water ingestion	3.18E-10	0	0	0	3.18E-10
Total	9.12E-07	0	0	5.73E-09	9.12E-07
		WAG 9			
Fish consumption	0	3.76E-08	2.24E-07	0	2.62E-07
Milk consumption	0	8.26E-09	4.06E-07	0	4.14E-07
Beef consumption	0	1.35E-08	5.52E-07	0	5.65E-07
Vegetable consumption	0	5.25E-10	1.08E-07	0	1.08E-07
Drinking water	0	1.31E-09	2.6E-07	0	2.61E-07
Bathing	0	5.57E-14	9.29E-13	0	9.85E-13
Swimming	0	6.88E-12	9.05E-13	0	7.78E-12
Boating	0	4.58E-12	6.04E-13	0	5.19E-12
Shoreline activity	0	4.88E-08	3.41E-08	0	8.29E-08
Irrigated soil	0	2.07E-09	1.44E-09	0	3.51E-09
Soil ingestion	0	0	0	0	0
Water ingestion	0	4.91E-11	9.75E-09	0	9.8E-09
Total	0	1.12E-07	1.59E-06	0	1.71E-06

[a]The ^{3}H exposure in the ORNL/ESD method is simplified. It is assumed that one-third of the body water in a human receptor is derived from surface water at the location of interest (i.e., WAG 2 or Clinch River Mile 9.5). Hence, no pathway-specific doses are reported here.

Table A.2. Calculated yearly doses (Sv/year) for each WAG and exposure pathway for the WAG 2 receptor

Exposure pathway	^{60}Co	^{137}Cs	^{90}Sr	^{3}H[a]	Total
		All WAGs			
Fish consumption	1.79E-05	1.79E-03	3.59E-04	0.00E+00	2.17E-03
Milk consumption	6.36E-06	3.94E-04	6.49E-04	0.00E+00	1.05E-03
Beef consumption	2.59E-05	6.43E-04	8.82E-04	0.00E+00	1.55E-03
Deer consumption	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Vegetable consumption	1.67E-06	2.50E-05	1.72E-04	0.00E+00	1.99E-04
Drinking water	4.16E-06	6.24E-05	4.16E-04	0.00E+00	4.82E-04
Bathing	1.43E-11	2.65E-09	1.49E-09	0.00E+00	4.15E-09
Swimming	1.91E-07	3.27E-07	1.45E-09	0.00E+00	5.20E-07
Boating	1.27E-07	2.18E-07	9.65E-10	0.00E+00	3.46E-07
Shoreline activity	3.73E-04	2.33E-03	5.46E-05	0.00E+00	2.75E-03
Irrigated soil	1.68E-05	9.85E-05	2.31E-06	0.00E+00	1.18E-04
Soil ingestion	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water ingestion	1.56E-07	2.34E-06	1.56E-05	0.00E+00	1.81E-05
Total	4.47E-04	5.34E-03	2.55E-03	1.71×10^{-4}	8.34E-03
		WAG 1			
Fish consumption	9.99E-06	1.31E-03	1.25E-04	0.00E+00	1.44E-03
Milk consumption	3.54E-06	2.87E-04	2.26E-04	0.00E+00	5.16E-04
Beef consumption	1.44E-05	4.69E-04	3.07E-04	0.00E+00	7.90E-04
Vegetable consumption	9.28E-07	1.82E-05	5.99E-05	0.00E+00	7.90E-05
Drinking water	2.32E-06	4.55E-05	1.45E-04	0.00E+00	1.92E-04
Bathing	7.98E-12	1.93E-09	5.17E-10	0.00E+00	2.46E-09
Swimming	1.06E-07	2.39E-07	5.04E-10	0.00E+00	3.45E-07
Boating	7.08E-08	1.59E-07	3.36E-10	0.00E+00	2.30E-07
Shoreline activity	2.08E-04	1.70E-03	1.90E-05	0.00E+00	1.92E-03
Irrigated soil	9.36E-06	7.18E-05	8.04E-07	0.00E+00	8.19E-05
Soil ingestion	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water ingestion	8.69E-08	1.71E-06	5.43E-06	0.00E+00	7.22E-06
Total	2.49E-04	3.90E-03	8.87E-04	4.14E-06	5.04E-03
		WAG 2			
Fish consumption	0.00E+00	1.14E-04	4.99E-06	0.00E+00	1.19E-04
Milk consumption	0.00E+00	2.50E-05	9.03E-06	0.00E+00	3.40E-05
Beef consumption	0.00E+00	4.09E-05	1.23E-05	0.00E+00	5.32E-05
Deer consumption	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Vegetable consumption	0.00E+00	1.59E-06	2.40E-06	0.00E+00	3.98E-06
Drinking water	0.00E+00	3.96E-06	5.79E-06	0.00E+00	9.75E-06
Bathing	0.00E+00	1.69E-10	2.07E-11	0.00E+00	1.89E-10
Swimming	0.00E+00	2.08E-08	2.02E-11	0.00E+00	2.08E-08
Boating	0.00E+00	1.39E-08	1.34E-11	0.00E+00	1.39E-08
Shoreline activity	0.00E+00	1.48E-04	7.59E-07	0.00E+00	1.49E-04

Table A.2 (continued)

Exposure pathway	^{60}Co	^{137}Cs	^{90}Sr	^{3}H[a]	Total
Irrigated soil	0.00E+00	6.26E-06	3.22E-08	0.00E+00	6.29E-06
Soil ingestion	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water ingestion	0.00E+00	1.49E-07	2.17E-07	0.00E+00	3.66E-07
Total	0.00E+00	3.40E-04	3.55E-05	3.18E-06	3.78E-04
		WAG 3			
Fish consumption	0.00E+00	8.77E-06	9.24E-06	0.00E+00	1.80E-05
Milk consumption	0.00E+00	1.92E-06	1.67E-05	0.00E+00	1.86E-05
Beef consumption	0.00E+00	3.14E-06	2.27E-05	0.00E+00	2.59E-05
Vegetable consumption	0.00E+00	1.22E-07	4.43E-06	0.00E+00	4.55E-06
Drinking water	0.00E+00	3.05E-07	1.07E-05	0.00E+00	1.10E-05
Bathing	0.00E+00	1.30E-11	3.83E-11	0.00E+00	5.12E-11
Swimming	0.00E+00	1.60E-09	3.73E-11	0.00E+00	1.64E-09
Boating	0.00E+00	1.07E-09	2.49E-11	0.00E+00	1.09E-09
Shoreline activity	0.00E+00	1.14E-05	1.40E-06	0.00E+00	1.28E-05
Irrigated soil	0.00E+00	4.81E-07	5.95E-08	0.00E+00	5.41E-07
Soil ingestion	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water ingestion	0.00E+00	1.14E-08	4.02E-07	0.00E+00	4.13E-07
TotaL	0.00E+00	2.61E-05	6.57E-05	0.00E+00	9.18E-05
		WAG 4			
Fish consumption	0.00E+00	1.19E-04	1.12E-04	0.00E+00	2.31E-04
Milk consumption	0.00E+00	2.61E-05	2.03E-04	0.00E+00	2.29E-04
Beef consumption	0.00E+00	4.26E-05	2.76E-04	0.00E+00	3.19E-04
Vegetable consumption	0.00E+00	1.66E-06	5.39E-05	0.00E+00	5.55E-05
Drinking water	0.00E+00	4.13E-06	1.30E-04	0.00E+00	1.34E-04
Bathing	0.00E+00	1.76E-10	4.65E-10	0.00E+00	6.41E-10
Swimming	0.00E+00	2.17E-08	4.53E-10	0.00E+00	2.22E-08
Boating	0.00E+00	1.45E-08	3.02E-10	0.00E+00	1.48E-08
Shoreline activity	0.00E+00	1.54E-04	1.71E-05	0.00E+00	1.71E-04
Irrigated soil	0.00E+00	6.53E-06	7.23E-07	0.00E+00	7.25E-06
Soil ingestion	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water ingestion	0.00E+00	1.55E-07	4.88E-06	0.00E+00	5.04E-06
Total	0.00E+00	3.54E-04	7.99E-04	3.60E-05	1.19E-03
		WAG 5			
Fish consumption	0.00E+00	8.17E-06	4.87E-05	0.00E+00	5.68E-05
Milk consumption	0.00E+00	1.79E-06	8.81E-05	0.00E+00	8.99E-05
Beef consumption	0.00E+00	2.93E-06	1.20E-04	0.00E+00	1.23E-04
Vegetable consumption	0.00E+00	1.14E-07	2.34E-05	0.00E+00	2.35E-05
Drinking water	0.00E+00	2.84E-07	5.64E-05	0.00E+00	5.67E-05
Bathing	0.00E+00	1.21E-11	2.02E-10	0.00E+00	2.14E-10
Swimming	0.00E+00	1.49E-09	1.97E-10	0.00E+00	1.69E-09
Boating	0.00E+00	9.95E-10	1.31E-10	0.00E+00	1.13E-09
Shoreline activity	0.00E+00	1.06E-05	7.40E-06	0.00E+00	1.80E-05
Irrigated soil	0.00E+00	4.49E-07	3.13E-07	0.00E+00	7.62E-07

Table A.2 (continued)

Exposure pathway	^{60}Co	^{137}Cs	^{90}Sr	^{3}H[a]	Total
Soil ingestion	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water ingestion	0.00E+00	1.07E-08	2.12E-06	0.00E+00	2.13E-06
Total	0.00E+00	2.44E-05	3.46E-04	1.20E-04	4.91E-04
		WAG 6			
Fish consumption	0.00E+00	1.14E-04	4.99E-06	0.00E+00	1.19E-04
Milk consumption	0.00E+00	2.50E-05	9.03E-06	0.00E+00	3.40E-05
Beef consumption	0.00E+00	4.09E-05	1.23E-05	0.00E+00	5.32E-05
Vegetable consumption	0.00E+00	1.59E-06	2.40E-06	0.00E+00	3.98E-06
Drinking water	0.00E+00	3.96E-06	5.79E-06	0.00E+00	9.75E-06
Bathing	0.00E+00	1.69E-10	2.07E-11	0.00E+00	1.89E-10
Swimming	0.00E+00	2.08E-08	2.02E-11	0.00E+00	2.08E-08
Boating	0.00E+00	1.39E-08	1.34E-11	0.00E+00	1.39E-08
Shoreline activity	0.00E+00	1.48E-04	7.59E-07	0.00E+00	1.49E-04
Irrigated soil	0.00E+00	6.26E-06	3.22E-08	0.00E+00	6.29E-06
Soil ingestion	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water ingestion	0.00E+00	1.49E-07	2.17E-07	0.00E+00	3.66E-07
Total	0.00E+00	3.40E-04	3.55E-05	3.18E-06	3.78E-04
		WAG 7			
Fish consumption	0.00E+00	1.14E-04	4.99E-06	0.00E+00	1.19E-04
Milk consumption	0.00E+00	2.50E-05	9.03E-06	0.00E+00	3.40E-05
Beef consumption	0.00E+00	4.09E-05	1.23E-05	0.00E+00	5.32E-05
Vegetable consumption	0.00E+00	1.59E-06	2.40E-06	0.00E+00	3.98E-06
Drinking water	0.00E+00	3.96E-06	5.79E-06	0.00E+00	9.75E-06
Bathing	0.00E+00	1.69E-10	2.07E-11	0.00E+00	1.89E-10
Swimming	0.00E+00	2.08E-08	2.02E-11	0.00E+00	2.08E-08
Boating	0.00E+00	1.39E-08	1.34E-11	0.00E+00	1.39E-08
Shoreline activity	0.00E+00	1.48E-04	7.59E-07	0.00E+00	1.49E-04
Irrigated soil	0.00E+00	6.26E-06	3.22E-08	0.00E+00	6.29E-06
Soil ingestion	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water ingestion	0.00E+00	1.49E-07	2.17E-07	0.00E+00	3.66E-07
Total	0.00E+00	3.40E-04	3.55E-05	3.18E-06	3.78E-04
		WAG 8			
Fish consumption	7.94E-06	0.00E+00	0.00E+00	0.00E+00	7.94E-06
Milk consumption	2.82E-06	0.00E+00	0.00E+00	0.00E+00	2.82E-06
Beef consumption	1.15E-05	0.00E+00	0.00E+00	0.00E+00	1.15E-05
Vegetable consumption	7.38E-07	0.00E+00	0.00E+00	0.00E+00	7.38E-07
Drinking water	1.84E-06	0.00E+00	0.00E+00	0.00E+00	1.84E-06
Bathing	6.35E-12	0.00E+00	0.00E+00	0.00E+00	6.35E-12
Swimming	8.44E-08	0.00E+00	0.00E+00	0.00E+00	8.44E-08
Boating	5.63E-08	0.00E+00	0.00E+00	0.00E+00	5.63E-08
Shoreline activity	1.65E-04	0.00E+00	0.00E+00	0.00E+00	1.65E-04
Irrigated soil	7.44E-06	0.00E+00	0.00E+00	0.00E+00	7.44E-06
Soil ingestion	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table A.2 (continued)

Exposure pathway	^{60}Co	^{137}Cs	^{90}Sr	^{3}H[a]	Total
Water ingestion	6.91E-08	0.00E+00	0.00E+00	0.00E+00	6.91E-08
Total	1.98E-04	0.00E+00	0.00E+00	1.24E-06	1.99E-04
		WAG 9			
Fish consumption	0.00E+00	8.17E-06	4.87E-05	0.00E+00	5.68E-05
Milk consumption	0.00E+00	1.79E-06	8.81E-05	0.00E+00	8.99E-05
Beef consumption	0.00E+00	2.93E-06	1.20E-04	0.00E+00	1.23E-04
Vegetable consumption	0.00E+00	1.14E-07	2.34E-05	0.00E+00	2.35E-05
Drinking water	0.00E+00	2.84E-07	5.64E-05	0.00E+00	5.67E-05
Bathing	0.00E+00	1.21E-11	2.02E-10	0.00E+00	2.14E-10
Swimming	0.00E+00	1.49E-09	1.97E-10	0.00E+00	1.69E-09
Boating	0.00E+00	9.95E-10	1.31E-10	0.00E+00	1.13E-09
Shoreline activity	0.00E+00	1.06E-05	7.40E-06	0.00E+00	1.80E-05
Irrigated soil	0.00E+00	4.49E-07	3.13E-07	0.00E+00	7.62E-07
Soil ingestion	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water ingestion	0.00E+00	1.07E-08	2.12E-06	0.00E+00	2.13E-06
Total	0.00E+00	2.44E-05	3.46E-04	0.00E+00	3.70E-04

[a]The ^{3}H exposure in the ORNL/ESD method is simplified. It is assumed that one-third of the body water in a human receptor is derived from surface water at the location of interest (i.e., WAG 2 or Clinch River Mile 9.5). Hence, no pathway-specific doses are reported here.

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